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Coal Mining and Ground-Water Resources in the United States

A Report Prepared by the

Committee on Ground-Water Resources
in Relation to Coal Mining

Board on Mineral and Energy Resources

Commission on Natural Resources

National Research Council

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PREFACE

The relationship between water resources and fossil fuel development and use, and subsequent land reclamation and use, has been a source of much concern in this country in recent years. As a result, significant legislation and policy have been developed in response, especially since Project Independence was initiated by President Nixon in 1973. The response has focused on two issues:

(1) Water resources are not everywhere or always present in quantity or quality sufficient for the needs of the energy industry.

(2) Water-quality degradation may result from energy development and land reclamation activities.

The production of coal, one of the important fossil fuels, and its implications for environmental protection led to national legislation designed to ensure that such resources as ground water are not adversely affected in any permanent way by mining activities.

As a step toward improved understanding, the U.S. Bureau of Mines requested that the National Research Council undertake a study of relationships between ground-water resources and coal mining. In response, the Board on Mineral and Energy Resources of the NRC's Commission on Natural Resources convened a Committee on Ground-Water Resources in Relation to Coal Mining. This volume is the Committee's report on its task.

The Committee realizes that a generic study of this kind runs the risk of giving too little attention to any number of issues that deserve fullscale treatment on their own merits. Nevertheless, the Committee made every effort to identify and discuss fully in the report the major issues related to impacts of coal mining on ground water.

In approaching its task, the Committee divided into subcommittees to concentrate on the following topics: (1) Hydrogeology and Water Resources; (2) Eastern Coal Mining and Reclamation; and (3) Western Coal Mining and Reclamation. Once attention to the more technical aspects of the study was underway, the Committee formed a Panel on

water and to study appropriate institutions for dealing with management and regulation of mining and ground water. As the study progressed, original assignments were modified to focus Committee members' expertise more closely upon specific subjects. An editorial subcommittee was also formed to oversee the writing of the report.

The Committee wishes to express thanks to the U.S. Bureau of Mines for their financial support and to the Committee's liaison representatives from the Bureau of Mines, U.S. Geological Survey, and the U.S. Environmental Protection Agency.

CHAPTER 1

CONCLUSIONS AND RECOMMENDATIONS

INTRODUCTION

Objectives of the Study

The purpose of this report is to examine the expansion and geographical redirection of coal mining now occurring in the United States, its effects on ground water, and the environmental and socioeconomic impacts of those effects. (Throughout the report, the term "effect" is used in reference to the changes in ground-water resources that result directly from a mining activity. The term "impact" refers to the ensuing environmental and socioeconomic consequences of the ground-water changes.)

Scope of the Study

The study could have been limited to the effects coal mining might have on the quantity and quality of ground-water resources. However, such an approach would address only technical issues and leave the reader with limited guidance and perspective. Therefore, the scope of this examination has been broadened to enable the reader to see coal mining as one of many competing uses for the nation's ground-water resources. To that end, the report addresses ground-water use, ground-water supplies and availability, principles that govern the functioning of hydrogeologic systems, and the institutional framework for ground-water allocation.

Because of the geological, hydrological, climatic, and water-rights differences between the eastern and western United States, the study includes separate examinations of the specific ground-water implications of coal mining in both regions. The 100th meridian was selected as the boundary between the East and the West. Texas and the Gulf Coast are included in the eastern zone. Alaska is not covered in the report because the NRC Committee on Alaskan Coal Mining and Reclamation reported on that subject (National Research Council 1980).

However, it does not include ground-water effects that may resu
transportation or consumption of coal or from any other coal-r
activity, unless that activity is an integral part of operatio
mine site.

This report describes how methods of coal extraction may a
ground water and assesses methods for mitigating adverse effec
and after mining. It includes both scientific explanations of
mining can affect the quality and quantity of ground water in
representative settings, along with technical assessments of s
coal basins and mining activities east and west of the 100th m
Two issues raised by the 1977 Surface Mining Control and Recla
Act (Public Law 95-87)--the restoration of hydrologic balance
abandoned lands, and the protection of alluvial valley floors-
discussed as well.

The report appraises the state of knowledge within the dis
of hydrogeology. Directions for future research and monitorin
programs, data management, predictive modeling, and manpower a
training needs are described. Special consideration was given
current and planned research in the broad area of coal mining
ground-water relationships. Accordingly, the Committee commis
study of ongoing research in these areas, which catalogued mor
600 projects providing an inventory of present and projected f
and state-funded research. This information was used by the c
to help ascertain directions into which future research progra
most beneficially channeled.

CONCLUSIONS AND RECOMMENDATIONS

Coal mining has produced the obvious benefits of increased
supplies and opportunities for employment. However, it has al
entailed costs, including changes in ground-water resources, w
had adverse impacts upon the natural environment and ground-wa
users. To date, the ground-water effects and their attendant
impacts--with the exception of acid mine drainage in the easte
States--have been confined to relatively small areas. In futu
decades, increased levels of coal mining, together with greate
reliance on ground-water resources for other purposes, are exp
increase the diversity and severity of the effects and impacts
levels of regional or national concern.

Mining affects both ground-water quantity and quality. Th
of mining on ground-water levels and flow normally occur quick
can be identified and monitored. Equilibrium in ground-water
and flow regimes is often readily re-established, but changes
ground-water quality can be long lasting and difficult to reve
Furthermore, the exact nature of future ground-water quality
degradation as a result of mining cannot always be anticipated
effects of mining cannot be identified until long afterward, a
time lapse makes mitigation difficult.

presents a difficult problem for public policy. Because changes often are detected only after it is too late to manage them, the usual approach of monitoring effects and taking appropriate action based on the results of that monitoring will be ineffective in many cases. Thus, an approach that anticipates what may occur and keys action to those expectations will be required.

The effects of coal mining on ground water must always be viewed in relation to the character and magnitude of other ground-water uses (which vary spatially and temporally) and in relation to the value placed on the ground-water resource.

Effects of Coal Mining on Ground-Water Quantity

Dewatering is a consequence of mining that can occur in several ways. In surface mining, for example, an aquifer may be physically removed, or the mine may be dewatered purposely to provide a dry working face. This, in turn, may induce inflow from other aquifers, causing ground-water levels to decline in adjacent areas. Mine shafts may also drain nearby areas and cause shallow wells to become dry while increasing recharge to deeper aquifers. In those cases, runoff rapidly infiltrates the ground-water system and then may flow to the surface elsewhere to discharge into a watercourse. Similar effects can be caused by fractures resulting from blasting, by caverns created by underground coal gasification, and by subsidence. In some underground mining situations (particularly in Appalachian settings), mine workings or associated subsidence become permanent ground-water drains. Surface mines, when backfilled, limit the changes in ground-water quantity caused by dewatering, except where the thick underclays are removed during mining operations. Declines in ground-water level have rarely been observed more than 3 miles from the point of disturbance; most declines occur within 1 mile.

Once underground or surface-mining operations have been completed, changes in ground-water quantity usually develop. The changes result from the alteration of ground-water recharge conditions and aquifer characteristics. Natural aquifers destroyed by surface mining usually are replaced by mine spoils, which then become aquifers. In most situations (except in parts of the Gulf Coast lignite fields), mine spoil aquifers transmit ground water at least as readily as the strata replaced, thus acting more as conduits than as barriers to ground-water flow. Impacts of the increased transmission of water are expected to be beneficial, except where ground water of undesirable quality is generated.

Despite a basic understanding of the general response of ground water to mining, several aspects of the overall problem remain that require further understanding. Therefore the Committee makes the following recommendations:

- <u>Further research should be conducted on the movement of water in the unsaturated zone of various hydrologic settings in both undisturbed and reclaimed lands.</u>

overburden for creation of favorable conditions of ground-water flow and aquifer behavior. Additionally, furt research should be conducted on the design of artificial aquifers during the reclamation process and on the hydrolog system in the mine-spoil aquifers.

- More research should be conducted on the nature of ground-water flow in fractured or jointed sedimentary rocks particularly in coal beds.

- The effects of underground mining on ground-water quantity, especially regarding subsidence and backfill operations, should be the object of further research.

- An assessment should be made of the effects of pre-mine exploration drilling and mine plan drilling on hydrogeologi systems.

Effects of Coal Mining on Ground-Water Quality

Mining activities cause changes in the chemical composition of ground water. In fact, the change in ground-water quality is the mo significant alteration of the ground-water resource resulting from c mine operations. Mining substantially alters the relative influence various geochemical processes and results in ground water with different concentrations of various chemical constituents than would normally be present. In some cases, the changes will impair the quality of the ground water for current or future uses; whereas in others, the changes will have no significant influence on water use, changes may be so slight as to be difficult to detect.

Effects on ground-water quality vary depending on mining techniq chemical characteristics of overburden materials, and type of coal. the East, effects are more site-specific than in the West, because t geology, topography, and climate vary more. In eastern basins, mini situations are so complex and variable that generalizations are not applicable to specific sites. In arid basins in the West, local variabilities result in some complexity, but the existence of persistent flow regimes permits analyses of effects that can be extrapolated spatially.

The greatest potential for degradation of water quality in the E occurs where the overburden contains appreciable concentrations of pyrite (FeS_2), which, when oxidized, is a strong acid producer. Eve very small amounts of pyrite in a carbonate-deficient geologic environment can, when the hydrological and geochemical conditions ar suitable for oxidation, lead to production of iron-sulfate, and sulfuric acid.

Although acid mine drainage remains a concern in the East, the adoption of state reclamation laws and federally mandated clean-wate regulations in recent years has resulted in a significant

decrease in acid mine drainage. The continued implementation of PL 95-87 is expected to further this improvement.

Reduction in acid mine drainage can be achieved either by initiating chemical reactions that deter oxidation of pyrite or by neutralizing the resulting acid. The treatments include such steps as inundating acidic materials, placing topsoil over the materials and establishing a vegetative cover to reduce runoff rates, and reducing the available oxygen by adding decaying organic matter, which also helps increase the alkalinity available for acid neutralization.

In some underground mines in the East, the impact on ground-water quality is relatively small because the mine entry shaft to the coal seam is not connected or is left open to the land surface after mine operations cease. In other areas, where mine openings do connect with the surface, ground-water quality degradation is more likely and may be a persistent problem.

In the West, ground water in the spoils of surface-mined land also acquires high major-ion concentrations as it interacts with the disturbed geological materials. However, the increase in major ions occurs because of the flushing out of soluble salts from the spoil and because of the oxidation of pyrite. Ground water in western mined areas seldom becomes acidic, usually because carbonate minerals in the overburden provide long-term neutralization.

On the other hand, in western surface-mined land, the sulfate concentration can be so high that the ground water in the spoil becomes unfit for human or agricultural use.

Ground water in the spoils of surface-mined land in the West acquires sulfate salts slowly because of: (a) the infrequency of infiltration, (b) the slow rate of rise of the water table in the spoil, (c) the slow diffusion of salts from the spoil materials to the water moving through the large void spaces or fractures, and (d) the slow rate of oxidation of pyrite. Years or even decades can pass before ground water in the spoils attains its maximum concentration of salts. If the sulfate salt is derived mainly from the solubilization of salts in the spoils (i.e., salts that existed in the overburden prior to mining), the ground-water quality will improve with time. Once the salts are completely transferred from the solids to the ground water, new infiltration and flow through the spoil can result in an improvement in ground-water quality. Concurrently, the salts flushed from the spoil are transported into ground-water zones outside of the mined area or are discharged into surface water. If pyrite oxidation is an important cause of increased sulfate in the ground water, the rate at which the maximum increase occurs may be slower than for salt solubilization alone. Ground-water quality recovery may prove to be slow after severe increases in dissolved sulfate concentrations develop.

Underground coal gasification is a special problem that has the greatest potential effect on ground-water quality because it may lead to the mobilization of toxic hydrocarbons and other elements in the ground-water system. Because data are limited, however, little is known of this phenomenon.

Hydrogeochemical factors are time dependent and cause short- and

must pass before maximum change in ground-water quality is achieved varies from years to decades or longer. Also, because ground-water flow is generally slow, centuries may pass before the contamination enclave extends beyond the mined area or before surface waters are affected by the inflow of contaminated ground water. If contaminate water travels a long distance in the ground-water zone before reachi surface waters, the contaminant concentrations may gradually be considerably reduced by the subsurface system.

Recognition of the time scale is important, because ground-wate monitoring will not, in some areas, provide an adequate indication c the effects of mining until long after the areas have been mined anc backfilled and reclamation is complete. Thus, real-time monitoring cannot be relied on to signal impending changes soon enough to allov appropriate adjustments in mining procedures or reclamation measure: Consequently, evaluation of effects of mining on ground-water qualit must rely more on prediction than on real-time monitoring.

Numerous mathematical models were developed in the 1970s to prec the migration of contaminants in ground water under the influence o: flow, dispersion, and geochemical retardation. However, the models have not been used significantly in predicting contaminant migratio from spoil in ground-water zones beyond the mine site.

Accordingly, the Committee makes the following recommendations:

- Additional information should be acquired on the chemical composition of spoil ground water at abandoned and active mines and in various hydrogeologic and climatic settings.

- The long-term movement of contaminated spoil water in regi ground-water flow systems should be evaluated on a site-by-site basis, and predictions about the eventual influence of seepage into surface waters should be develop

- The nature of the geochemical interactions between ground water and spoil material should be determined under contro laboratory conditions; the research should include experim designed to elucidate effects that will occur in the field only over long periods of time but can be accelerated in t laboratory.

- Improved computational hydrogeochemical models should be developed that will make it possible to use field and laboratory information to predict changes in ground-water quality, in mine spoils, over time spans ranging from year centuries; the models must be able to account for processe that occur both above and below the water table.

- Additional research should be conducted on the selective placement of overburden materials that minimize degradatio ground-water quality.

- Research should be conducted on effects of underground mining on ground-water quality, especially effects of mine subsidence and backfill operations.

- Research should be conducted to develop an understanding of the technology of underground coal gasification and its effects on ground-water quality and to develop controls for minimizing adverse changes in water-quality.

- Research should be conducted to assess effects of pre-mine exploration drilling and mine plan drilling on ground-water quality.

Waste Disposal in Surface-Mined Lands

Disposal of wastes in surface-mined lands has been practiced since surface mining for coal began. Indiscriminate dumping of waste material has adversely affected ground-water resources.

In recent years, wastes from coal-cleaning plants and electric power plants have been placed in both unused surface mines and underground mines. If properly handled, such materials may not cause deleterious effects on ground water. However, the burial of large amounts of wastes in inappropriate hydrogeologic settings, or with inadequate equipment or handling, can contribute to long-term water-quality problems.

Surface-mined areas can be considered a potential resource not only for water supply, recreation, and agriculture, but also for disposal of certain kinds of wastes, if that disposal is conducted under appropriate conditions.

Accordingly, the Committee makes the following recommendations:

- In order to bury waste material properly in abandoned mines, research evaluations should be conducted through joint government and industry research programs.

- Data from these studies should be published and distributed widely within industry and among government agencies.

- Appropriate guidelines for waste disposal should be developed based on applied research data.

Abandoned Lands

For years, surface and underground mining operations have disturbed land and water resources, but until recently there have been no nation-wide attempts at reclamation. Acidic or poorly vegetated spoil banks, burning waste piles, mine subsidence, abandoned coal preparation plants, uncovered gob or slurry areas, impoundments containing acidic water, and degraded acid mine drainages exist in many mining areas

throughout the nation. These areas can have an adverse effect on any associated ground-water resource. Reclamation plans should take into account the hydrogeologic system, rather than just the land surface. Currently, no known reclamation design of mined land attempts to minimize the degradation of ground-water quality. Without proper assessment, adverse effects to the ground-water system may increase. Thus, efforts to restore abandoned mine lands should weigh the potential benefits against the potential for creating additional adverse hydrologic impacts.

Accordingly, the Committee makes the following recommendation:

- Reclamation plans for abandoned lands should include consideration of possible effects upon ground-water resources.

Impacts of Coal Mining on Ground-Water Users

Because ground water and surface water are interrelated, the impacts of coal mining affect both surface-water and ground-water users. The effects of mining on ground water--such as acid mine drainage in the eastern United States, salinity and sulfate buildup in the western United States, or depletion and augmentation of ground-water resources in many areas--can affect the use of ground or surface water for such purposes as irrigation, domestic water supply, and maintenance of fish and wildlife resources.

Effects of coal mining on water quantity are likely to be temporary, while its effects on water quality will be more persistent; but in either case, impacts of the effects on ground-water users are likely to be long term rather than short term. The situation is exacerbated by existing programs designed only to reclaim the land, rather than to enhance water quantity or quality.

The Committee therefore makes the following recommendation:

- Research should be undertaken on methods and applications for estimating potential socioeconomic and environmental impacts of ground-water changes due to coal mining.

Options for the Control of Impacts on Ground-Water Users

Options available for dealing with adverse impacts caused by changes in ground water due to coal mining include the following:

1. Do nothing: accept all impacts without mitigation.

natural hydrological and geochemical processes work toward equilibrium.)

4. Mitigate effects and thus reduce impacts by diverting undesirable outputs into more productive channels (e.g., byproduct recovery instead of waste disposal).

5. Mitigate effects and thus reduce impacts by changing mining or reclamation methods and inputs (e.g., when existing land reclamation methods are typically designed primarily to reclaim the land, other methods, such as selective replacement of overburden, are needed that will pay greater heed to aspects of water quality and quantity).

6. Mitigate effects and thus reduce impacts by prohibiting mining.

In view of these options, the Committee makes the following recommendations:

- Research should be carried out that identifies the relative advantages and disadvantages of various methods of controlling impacts of coal mining on ground water.

- Research should be undertaken to develop and evaluate means of mitigating impacts. For example, effective methods of controlling the quality of ground water in surface mines by selective placement of overburden should be studied through the use of models of ground-water chemistry.

- A better understanding should be gained of the resiliency, or natural recovery potential, of the various hydrogeologic systems within which coal mining may occur. This information is needed for estimating the potential of natural system recovery in ameliorating adverse impacts.

- Research should be conducted into the potential for recovery and use of coal-mining byproducts that cause contamination. Finding economic uses for such byproducts as trace elements or acid materials could produce a less costly or even profitable, way of ameliorating adverse impacts.

- Comparisons should be made of various mining technologies with respect to their effects on ground water and consequent adverse socioeconomic and environmental impacts. It is sometimes possible to choose between mining technologies for a single site. Where it is not possible, leasing policies or other institutional measures can be used to encourage the development of sites best suited to low-impact technology.

- Greater insight should be gained into conditions under which mining may produce such serious and unacceptable ground-water

related impacts that complete prohibition of mining shou considered. Such conditions usually occur on particular of sites (e.g., alluvial valley floors as referred to in 95-87) which could then be designated unsuitable for min

Institutional Control of Impacts

Existing institutional means for controlling impacts of coal on ground water combine different levels of government, types of standards, and implementation approaches. The initiative for ground-water quality control and for the control of surface-minin impacts has been assumed primarily by federal agencies, while the initiative for ground-water quantity allocation is primarily in p hands, subject to state water laws. Consideration of such institutional controls raises questions of scope and level of dec standards, and implementation.

Decision Scope. Controlling impacts of coal mining on ground deserves public and governmental attention, but the overall persp of ground-water problems should be maintained. There is no evide suggest that any socioeconomic or environmental impacts caused by changes in ground water due to coal mining are or may be so wides serious, or unique as to require special treatment, besides emplo general institutional measures to control ground-water use and ab

In the long term, special ground-water laws and regulations pertaining only to coal mining are probably unnecessary and undesirable, although current laws of this type, e.g., PL 95-87, required in the short term because of inadequacies of ground-wate controls in general.

The Committee makes the following recommendations regarding decision scope:

- Ground-water and surface-water use are treated as separa matters in both state water laws and federal water quali control programs. Yet much of the water in lakes and st is the result of ground-water inflow, and ground-water reservoirs are sometimes recharged by infiltration from surface-water supplies. Institutional means for coordin management of surface water and ground water are weak or missing in most parts of the United States, and efforts be made to strengthen or create them. This is largely a matter of changing state water law.

- Better means of coordinating quantitative ground-water allocation with control of ground-water quality are need One way of accomplishing this would be to specify quali controls in the state water rights system.

Decision Level. Ground-water use is controlled largely by st water laws. Such quantitative control is reasonably explicit and

states, employ a centralized regulatory approach. In some states, reliance on the two very different decision-making and implementation approaches for such closely interrelated areas renders decision making extremely difficult. Little institutional capability exists for achieving a desirable balance of interests in such a situation. By and large, impacts of coal mining on ground water are geographically confined, thus producing problems primarily at the local or state level.

Accordingly, the Committee makes the following recommendation:

- Given the weakness of current state laws and programs dealing with ground water, a federal role that would encourage and facilitate more rapid development of effective state controls is worth continued consideration. Such a role should influence the exercise of state powers and responsibilities without usurping them.

Standards. The types of standards or objectives used to control ground-water impacts vary widely. State water laws combine broad public-interest clauses with liabilty rules; both are forms of performance standards. Federal water-quality regulations also use performance standards (i.e., they seek to limit adverse effects of activities that use water). PL 95-87 employs both performance standards and design standards: the latter limit or specify what water users may or must do instead of regulating the consequences of their actions.

Performance standards are generally preferable to design standards because the focus is on a desired end rather than on the means. Thus, the water user is encouraged to adopt the most efficient means to attain a socially desired end. However, performance standards are useless where performance cannot be monitored; in such situations, only design standards should be considered. Neither performance standards nor design standards should be set at levels that are technologically unachievable or too costly. Design standards should not be used except when monitoring compliance with performance standards makes this choice unavoidable. Even in such cases, design standards should use all available information and should be revised as necessary to take advantage of new information.

American decision-making institutions, including both our economic markets and our political structure, are often fundamentally short sighted: they focus upon solving existing problems rather than those that may occur in the future. This is as true of ground-water institutions as of any others. In the case of ground-water resources, recovery is extremely slow, and problems may not be easily or quickly solved. Anticipating and avoiding the creation of problems in the first place may be easier, cheaper, and more effective than any remedial action. However, means for instituting such an approach are weak.

The Committee makes the following recommendations regarding standards:

- More emphasis should be given to developing performance standards for ground-water resources, particularly for allocating quantity. While performance standards for protecting ground-water quality are also desirable, desi standards may be the only workable option.

- Design standards probably should be incorporated in regulations rather than in statutes, because regulations be changed more easily as new methods of impact control developed.

- Legislative mandates to consider the interests of future generations should be investigated as possible additions state water laws. At present, water-use problems tend t seen as conflicts between parties currently at interest. Future-oriented mandates could apply to both ground-wate allocation decisions (well permits) and to the setting c standards within water-quality control programs.

Implementation. Implementation methods also vary. State wat laws rely upon a combination of regulations (permits are required are issued only if stipulated conditions are met) and liability r Both federal water-quality regulations and PL 95-87 employ the regulatory approach. Regulation is sometimes the only effective method, particularly when avoidance of critical and intolerable e is of paramount importance. However, regulation is inefficient a burdensome. Economic incentives, while no panacea, offer advanta acceptability and efficiency.

The Committee makes the following recommendations regarding implementation:

- Current policies for controlling the ground-water impact coal mining, and particularly those pertaining to the co of ground-water quality, should be reviewed to identify situations in which economic incentives could be used effectively.

- Research should be undertaken to develop public policy c that can deal with the uncertainty and possibly irrevers characteristics of prospective socioeconomic and enviror impacts.

Manpower Needs

scope; (2) the geology and civil engineering departments that offer such programs tend to give them a low priority; (3) many departments that offer hydrogeologic courses do not provide practical training; and (4) the interdisciplinary nature of the subject means that students need a broad mix of academic courses, not all of which are available at many universities.

Concerning manpower, the Committee makes the following recommendations:

- Quantitative evaluation of future manpower needs and the ability of universities to meet them should receive high priority.

- For the near term, a series of short courses in hydrogeology should be developed and offered as retraining for people with appropriate scientific and engineering backgrounds.

Information Needs

Regulations promulgated under PL 95-87 contain specific requirements for the assessment and monitoring of the hydrology and hydrogeology of coal-mining sites. The U.S. Geological Survey (USGS) has initiated a baseline hydrogeological program. Only a few states have programs oriented toward coal-mine hydrology, but through PL 95-87, new programs will be developed and existing ones expanded. For the first time, the private sector will be required to provide site-specific data, both on assessment and monitoring, thereby creating a large amount of new data. Computerized or other data-handling systems will have to be developed by the states to process this influx of data if they are to be used effectively. Thus, some coordinated effort should be developed to ensure that the funds spent by the federal, state, and private sectors take full advantage of the information generated.

Accordingly, the Committee makes the following recommendations:

- Greater effort should be made by individual states to create and maintain adequate, accessible data banks.

- More ground-water data should be generated from areas that contain coal resources and made accessible through state and federal files.

- In many areas, current data collection is limited to USGS cooperative studies; state agencies should expand this data base by developing other data-collection programs. State, federal, and private data collection programs should be coordinated.

National Research Council (1980) Surface Coal Mining in Alaska. Committee on Alaskan Coal Mining and Reclamation, Board on Mi[illegible] and Energy Resources, Commission on Natural Resources, Natio[illegible] Academy Press, Washington, D.C.

CHAPTER 2

THE GROUND-WATER RESOURCE IN THE UNITED STATES

INTRODUCTION

Humans are both biologically and culturally dependent on water. Not only do they use water for essential physiological needs (which constitute a tiny fraction of our water use), they also use it for many purposes that, while not strictly essential, have become key aspects of efforts to manage the environment and raise the standard of living.

Despite its general abundance, water is not always found in the place, at the time, or in the form that is desired. Part of the reason for this is human activity: people strive to grow crops and green lawns in semi-arid regions, and they attempt to use water simultaneously as a pure source and, deliberately or inadvertently, as a dump for wastes. Consequently, society faces an increasingly serious set of problems that are grouped under the heading of water management.

Ground water increasingly is turned to as surface supplies of freshwater are appropriated or, more commonly, because of seasonal unavailability or their being rendered unfit for use because of pollution. In the United States today, ground water is the major source of potable water and is a common source for both irrigation and industry. At the same time, however, some ground-water sources are being depleted or polluted to the point where such uses are adversely affected. Our increasing reliance on ground water, combined with its decreasing availability both as to quantity and quality, underscores the need to focus attention on this national resource.

FUNDAMENTALS OF HYDROGEOLOGY

In its broadest sense, hydrogeology is the study of interrelationships between water, rock, soil, and man, with an emphasis on ground water. Ground water has been described as subsurface or underground water, or sometimes as subterranean or phreatic water. It has been estimated that 94 percent of the earth's water resides in the oceans and the remaining 6 percent resides in, on, or above the earth's surface. Of this 6 percent, ground water accounts for approximately 4

percent, the polar caps and glaciers contain approximately 2 perc and the remaining water storage areas (such as lakes, rivers, and atmosphere and biosphere) account for less than 1 percent (Nace 1 Ground water makes up about 95 percent of freshwater supplies; la rivers, swamps, and reservoirs, 3.5 percent; and soil moisture, 1 percent. The figures represent a static condition of water balar the earth. However, water is in constant motion: river water ha turnover period of weeks and ground water has residence times rar from a few years to thousands of years.

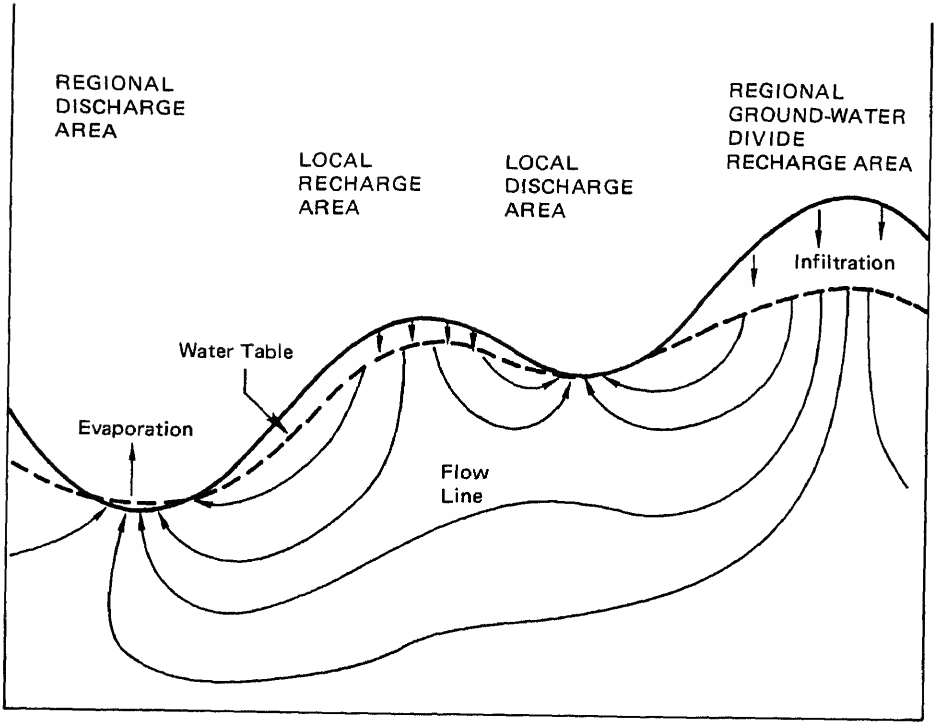
Ground water typically is considered a renewable resource, al the rates of replenishment and natural discharge vary greatly bet humid and arid regions. In both regions, ground water sometimes mined, i.e., the rate of withdrawal exceeds the rate of natural recharge. An effect of mining can be near exhaustion of ground-w supply (common in the arid West) or the intrusion of poor quality (common in some coastal areas). Once it is mined to the point of exhaustion or to the point where poor quality water has intruded, ground water may not be naturally renewed in less than hundreds c thousands of years.

Essential to an understanding of ground water and its relatic to other parts of the hydrogeologic cycle is the concept of stora Reservoirs that store water vary greatly in type and character ar either natural or man-made. Natural and man-made ponds, lakes, a storage tanks provide water for many uses, and the quantity of wa available, like that in streams, varies with climate because it i dependent largely upon precipitation. Storage in surface reservo during periods of high precipitation runoff, to meet continuing d for water in dry periods, has long been a water-management practi the nation.

A second type of storage, soil moisture, involves large quant of water that act as an interface between precipitation and other of the hydrologic cycle. The soil-moisture reservoir provides th first opportunity for water storage and management in many parts nation where the largest supply of water and the greatest opportu for storage lie in the ground-water system. The amount of water depends on precipitation; on the texture, structure, and slope of soil; and on conservation, cropping, and other land-use practices

The ground-water system is naturally recharged by infiltratic water from the soil-moisture reservoir, from some streams or stre of them, and from ponded surface water. Thus, management practic that increase infiltration into the soil and to ground-water syst tend generally to deplete water in the surface-water component of hydrologic cycle. Water within the saturated ground-water zone m eventually be discharged again to the surface into streams or oth water bodies. If a ground-water system is saturated and no water withdrawn from it artificially, the rate of recharge balances the of discharge and the system remains saturated.

The water table, which is the upper surface of the saturated is generally a subdued replica of surface topography. Water move below the water table is along flow paths from recharge areas to discharge areas (see Figure 2.1). This pattern constitutes a du



SOURCE: Modified from S. M. Born and D. A. Stephenson, 1969.

FIGURE 2.1 Schematic Diagram of a Ground-Water Flow System

ground-water flow system. Once within such a system, water very slow rates compared to surface water. In addition, as through this system, its chemical quality changes according length of residence time within the subsurface and the chem of the materials it flows through.

In humid regions, most ground water is recharged from w miles to tens of miles from where the water eventually disc to the surface. In more arid regions, the distances ground travels typically are greater. An important concept is tha does not necessarily occur only where an aquifer crops out surface. Recharge sometimes occurs throughout the extent o aquifer.

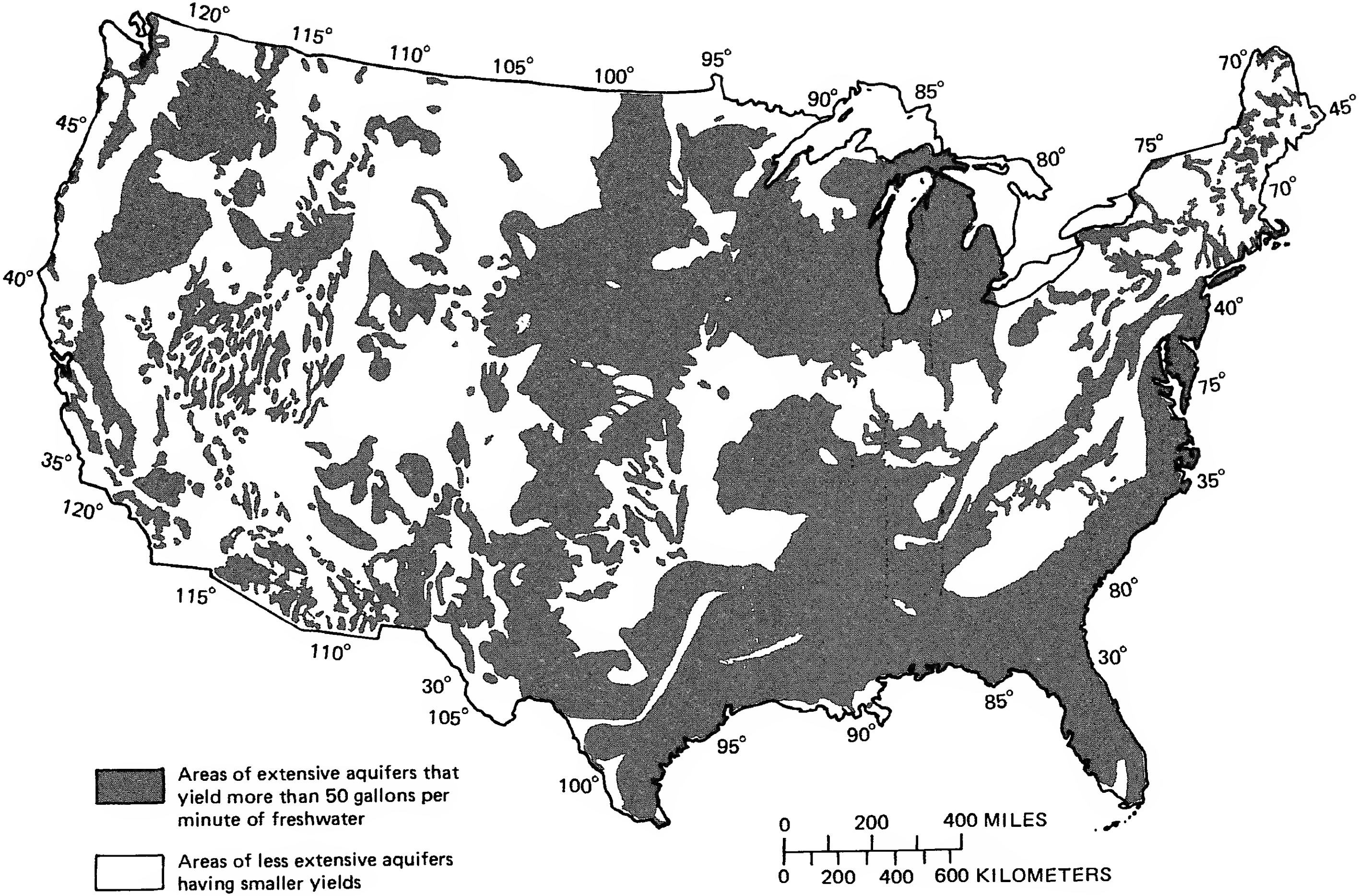
Saturated areas through which water moves are considere and typically include such porous materials as alluvium, sa limestone, and even coal. Some coals, however, are relati nonporous; they are called "aquitards" because water moves at very slow rates. This also is common for most shales a unfractured rock materials. In some rock, however, stress systems of fractures, or joints, through which water can m

GROUND-WATER SUPPLIES

The ground-water resource of the United States is enorm 200 billion acre-feet or 65,000 trillion gallons. Approxi trillion gallons of ground water are estimated to be in st depths of less than 2,500 ft. in the United States (Water Council 1978). About 45 percent of this ground water in s about 16,000 trillion gallons, is considered available for a potential resource more than a thousand times greater th withdrawals. In many regions of the nation, current recha withdrawals, so that no net depletion occurs. Nationally, depletion of the resource is approximately 20.9 billion ga

Ground-water storage exceeds surface freshwater storag margin. Approximately seven times as much ground water is within 2,500 ft. of the ground surface as is found in all lakes in North America. The ground-water reserve is about volume of water discharged by the Mississippi River into t Mexico over the past 200 years (Water Resources Council 19

Ground-water storage and depletion vary widely through nation. More than one-third of the approximately 36,000 t gallons in storage is in the Rio Grande River Basin region 21 such regions in the United States. More than one-quart approximately 16,000 trillion gallons of ground water that withdrawn is in the south Atlantic-Gulf region. By contra California and Upper Colorado River basin regions possess supplies of ground water that can feasibly be withdrawn. illustrates the extent of aquifers yielding 50 gallons per freshwater. In general, more widespread and productive aq found in the humid East; those in the West tend to be less



SOURCE: Rickert and others, 1979.

FIGURE 2.2 Ground-Water Resources in the United States

Ground water is a reliable resource generally buffered from droughts that affect surface supplies and not subject to extreme temperature and quality fluctuations. In the United States, approximately 83 billion gallons of ground water per day, or 93 acre-feet for the year, were withdrawn in 1975 (Murray and Reeve 1977). That amount is 20 percent of the total annual withdrawal both surface and ground water. As shown in Table 2.1, irrigatio far the major use of ground water, accounting for almost 70 perc total withdrawals. Public water supply and industrial use accou most of the remaining 30 percent.

Reliance upon fresh surface-water supplies has declined proportionately in recent years, primarily because of restricted availability. Reliance upon saline surface-water supplies and ground-water supplies has increased to fill the gap. Between 19 1975, withdrawals of fresh ground water increased by 21.7 percen withdrawals of fresh surface water increased by only 5.1 percent Thus, the use of ground water is increasing not only in absolute but also as a fraction of total water use.

Ground water is a more important source of water supply for uses than for others. For example, it is used for less than 1 p of the nation's thermoelectric power generation and for less tha percent of other industrial uses of water; however, ground water represents 96 percent of all water used for rural domestic purpo more than 33 percent of the water used for irrigation and public supplies. Approximately half of the U.S. population relies on g water for domestic water supplies, whether through public system private wells, and ground water supplies the domestic water need out of 100 of the country's largest cities.

Nearly 17 million water wells exist throughout the nation, a almost 500,000 new ones are drilled each year. Ground water can recovered at almost any location in quantities large enough to p for the needs of a single dwelling, and more than one-third of t country is underlain by aquifers capable of providing 100,000 ga or more per day to single properly constructed wells.

Effect of Use on Ground-Water Quality

Given the increasing reliance on ground-water resources, it particularly alarming that its quality is being degraded by fertilizers, pesticides, industrial wastes, and sewage effluents degradation is the result of a ground-water use that does not ap Table 2.1 because it involves waste disposal rather than withdra water from the ground. Nonetheless, to use ground water for dis whether inadvertently or deliberately, is as much a use as is withdrawal and consumption. Indeed, in most parts of the United States, waste disposal is a competing use of greater consequence are conventional withdrawal-based uses, ec se was e di posal

TABLE 2.1 Ground-Water Use and Withdrawals in the United States in 1975

Use	Withdrawals (billions of gallons per day)
Public Supplies	11.0
Rural Use	
Domestic	2.7
Livestock	1.2
Irrigation	57.0
Industrial	
Thermoelectric power	1.4
Other	10.6
TOTAL	83.9

SOURCE: Murray and Reeves (1977)

Since 1971, numerous reports covering various geographi the United States, as well as a 1977 report to Congress, ha discussions of waste-disposal practices and their effects c ground-water quality (e.g., Miller, D.W. et al. 1974, Mill al. 1977; van der Leeden et al. 1975; Scalf et al. 1973; Fu Barton 1971; U.S. EPA 1977). From these reports, 19 activ potentially contribute to the degradation of ground-water c be identified: use of septic tanks and cesspools, petrole exploration and development, use of landfills and dumps, a practices, use of waste pits, ponds, and lagoons, natural l land application of wastes, artificial recharge, water wel construction, ground-water development, stockpiling of was use of storage tanks and pipelines, accidental spills, use wells and sumps, surface water use, highway salting, use o disposal wells, and air pollution.

Some activities, such as highway de-icing, are unique parts of the country; others are common to all areas. Abo of the population uses septic tanks or other means of subs disposal of domestic wastes. About 800 billion gallons of are discharged each year. Similar waste discharges from c industrial establishments further add to the volume.

Oil and gas production involves saltwater. Hundreds o of active and abandoned production wells, saltwater dispos flood wells, and holes drilled during exploration provide formation brines to contaminate ground water. Although th unlined saltwater pits has essentially been discontinued, will continue to contribute leached salts to ground water years. Since the 1950s, the oil and gas industry has stea techniques for controlling releases of saltwater to the en but earlier practices resulted in saltwater contamination persists today in many locations.

Landfills and waste impoundments pose a threat to grou quality; the threat is only now being understood, given th complexities in measuring and identifying the constituents comprise leachate from those facilities. The application and industrial sludges to the land is expected to increase importance because of anticipated regulations designed to discharges to streams by the year 1985. Recent investigat that a substantial percentage of industrial landfills cont ground water with organic chemicals. Pollutants not ordin considered in ground-water investigations are a big part o problem. An abundance of organic chemicals, in both liqui states, is associated with municipal and industrial wastes laboratories lack the capability to detect and evaluate th bacterial constituents of the wastes.

Of all the activities of man that affect ground water, is perhaps the most pervasive. Problems of ground water

coarse-textured soils; and (2) because of dry-land cropping procedures, increased concentrations of a wide spectrum of dissolved solids, including trace elements, occur in ground water.

In several areas of the West and Midwest, agricultural practices (primarily involving the use of fertilizer) are leading to higher concentrations of nitrate in ground water. Consequently, background levels of less than 1 mg/l have gradually increased to levels of tens of mg/l or higher. The recommended limit for nitrate in drinking water is 45 mg/l (expressed as NO_3^-). Nitrate is an undesirable constitutent in ground water used for drinking because it has been shown to be harmful to infants. Research has found that abnormally high concentrations of nitrate can also be harmful in water consumed by ducks and livestock, but no specific threshold concentration has been designated.

Agricultural processes generating saline ground water are similar to processes operating in mine spoils. One difference is that cropping practices tend to allow increased recharge through in-situ salt-bearing materials while mining practices result in the materials being placed where they will become saturated. Mining also results in materials becoming unconsolidated usually, and therefore more permeable by ground water.

Ground-Water/Surface-Water Relationship

Two major categories of ground-water use have been discussed: withdrawal and waste reception. A third category, which is more important yet too infrequently considered, is that of ground-water supply to surface-water bodies. Some 30 percent of the nation's stream flow in an average year is supplied by ground water that emerges from natural springs and other seepage outlets (Water Resources Council 1978). Thus, nearly one-third of the total United States fresh-water withdrawals, taken from surface sources, come indirectly from ground water.

Ground-water supply to surface water assumes additional special importance for two reasons beyond water supply. (1) Ground-water inflow is important to the seasonal continuity of stream flow. Without such inflow, many smaller streams would be seasonally intermittent (particularly in dry years), and stream levels would fluctuate more widely. (2) Ecosystem productivity would be far lower than it is now, especially without the natural storage and stream-regulating functions fulfilled by ground water.

Truly, the nation's ground-water resources constitute an immense, cost-free storage system which, in both scale and beneficial consequences, dwarfs man-made surface reservoir systems that have been created at great cost over many years. Moreover, essential uses of surface water (e.g., maintenance of aquatic and terrestrial ecosystems, water-based recreation, municipal water supplies, navigation, and hydroelectric power generation) depend upon sustained inflows of ground water.

GROUND-WATER ALLOCATION

If a resource is abundant relative to the demands placed up few disputes or conflicts over it are likely to occur. Where no competition exists, no social institutions are needed to contro use of the resource. Conversely, as demand increases, scarcity dictates control. Social institutions are devised to determine to whom available supplies of the resource will be allocated. I the nation's history, almost no laws or other means for resolvi disputes over ground-water use existed, because there were so fe disputes to settle. As the nation grew, however, conflicts ov ground water became more numerous, and a variety of means for re them emerged. This evolutionary development is still in progre is probably occurring more rapidly today than ever before.

Residents of the eastern United States have traditionally b that water is plentiful, while those in the West have experience in short supply. Consequently, different laws for water alloca evolved in the East and West. The eastern states created rules equal sharing of an abundant resource, while the western states developed systems for protecting individual property rights to a specific quantity of a resource that was limited and dwindling. Because access to surface water is easier than access to ground laws for surface-water allocation were developed before those fo ground water.

Historical Perspective on Water Law

Water law came initially from the courts (rather than legisl bodies) as disputes were settled between property owners. Some disputes concerned the use of ground water; more concerned the u surface water; few, if any, concerned both. As the rules evolv law regarding the use of ground water differed from that regardi use of surface water. Recently, a few courts recognized the hy cycle in making decisions on ground-water use and accepted the f that ground- and surface-water problems are interrelated [e.g., Cappaert v. United States, 426 U.S. 128, 142 (1976); State v. Mi Pipeline Construction, Inc., 63 Wis. 2d 278, 292, 217 N.W. 2d 3 (1974)]. However, old legal distinctions between the use of gro water and surface water tend to persist, and it may be many yea before they are entirely eliminated. Today, rights to ground wa based almost totally on state law. While all states follow one generally used patterns of rules, there may be substantial diff in specific laws among the various states (Trelease 1977).

Ground-Water Law

Historically, courts considered ground water to be part of possessed by the surface owner. It was property like an other

emoved by the owner for use, sale, or convenience. Only in rare nstances where it could be proven that ground water was being taken rom an underground flowing stream did the courts apply surface-water ules in determining the ownership of ground water. The courts escribed all other ground-water movement as "percolation" and made no ffort to understand ground-water movement or its relationship to urface water. A frequently quoted comment from a case decided in onnecticut in 1850 is "... its [ground water's] existence and rogress...cannot be known or regulated. It rises to great heights, nd moves collaterally, by influences beyond our comprehension. These nfluences are so secret, changeable and uncontrollable, we cannot ubject them to the regulations of law, nor build upon them a system of ules, as has been done, with streams upon the surface" [Roath v. riscoll, 20 Conn. 533, 541 (1850)].

Under what is known as the "English rule" or "common law rule," a roperty owner can pump as much ground water as he desires from his roperty without liability for damage that the resulting lowered water able causes to other property owners. The "American rule" (sometimes alled the "reasonable use rule") differs from the English rule only in hat it makes a pumper liable for damages caused to other property, if he pumped ground water is used on premises other than the area from hich it was pumped. The rule forces municipalities to pay damages used by municipal wells but gives little additional protection. An xample of the effect of the rules is found in a 1968 Maryland case in hich the dewatering of a rock quarry dried up wells, caused ubsidence, and resulted in the formation of sink holes on adjacent and. The court held that the quarry operator was acting within his egal rights and had no liability for any damage that resulted from umping ground water [Finley v. Teeter Stone, Inc., 251 Md. 428 A. 2d 06 (1968)].

Although the rules offered little protection to anyone other than he pumper, they met the needs of the vast majority of owners, as long s ground water was plentiful and was pumped only by wind or animal ower. The development of deeper wells and the use of ever larger umps powered by electricity and fossil fuels brought awareness of a eed to protect the rights of other property owners. As a result, the ourts in an increasing number of states have adopted significantly roadened versions of the reasonable use rule and are holding pumpers able if they unreasonably interfere with the rights of other property wners. A few states have adopted the "correlative rights rule" under hich the right to a share of the ground water correlates with the mper's share of surface ownership. The Restatement of Torts, Second, dopted by the American Law Institute states the current general rule o be as follows:

§ 858. Liability for Use of Ground Water

(a) the withdrawal of ground water unreasonably c
harm to a proprietor of neighboring land through loweri
water table or reducing artesian pressure

(b) the withdrawal of ground water exceeds the
proprietor's reasonable share of the annual supply or t
store of ground water, or

(c) the withdrawal of the ground water has a dire
substantial effect upon a watercourse or lake and
unreasonably causes harm to a person entitled to the us
its water.

(2) The determination of liability under clauses (a),
and (c) of Subsection (1) is governed by the principles
stated in §§ 850 to 857.

§ 850A. Reasonableness of the Use of Water

The determination of the reasonableness of a use of wat
depends upon a consideration of the interests of the ri
proprietor making the use, of any riparian proprietor h
by it and of society as a whole. Factors that affect t
determination include the following:

(a) the purpose of the use,

(b) the suitability of the use to the watercourse
lake,

(c) the economic value of the use,

(d) the social value of the use,

(e) the extent and amount of the harm it causes,

(f) the practicality of avoiding the harm by adju
the use or method of use of one proprietor or the othe

(g) the practicality of adjusting the quantity of
used by each proprietor,

(h) the protection of existing values of water us
land, investments and enterprises, and

(i) the justice of requiring the user causing ha
bear the loss.

Some states follow a similar rule (part of the law of n
imposing liability for causing unreasonable harm to other p
owners by polluting ground water.

Many states, rather than leaving development of ground-water law to he courts, have adopted legislation and created agencies to regulate he use of ground water and to allocate rights through a permit ystem. Usually, a state adopts a permit system only when demand for ound water exceeds the available supply, and as a result, the round-water resource is depleted. A permit system enables a state to rotect its ground-water supply by limiting the amount that can be ithdrawn under each permit and by refusing to issue additional permits hen a ground-water source is threatened.

In addition, many states have a few narrow statutes concerning pecific aspects of ground-water regulation, such as laws limiting or rohibiting recharge through wells or standards for well construction nd pump installation. Some states have enacted mining codes which nclude provisions intended to protect the quantity and quality of ound water.

No major federal act relates solely or primarily to ground-water otection or regulation, but several contain provisions relating to ts protection. For example, environmental impact statements required y the National Environmental Protection Act must consider any impacts n ground water anticipated to result from a proposed project or ctivity. The Federal Safe Drinking Water Act prohibits underground jection that endangers drinking water sources (42 U.S.C. §300h).

Of special interest to this report is the Surface Mining Control nd Reclamation Act of 1977 (Public Law 95-87), which contains numerous ovisions relating to ground water. Coal mining is the only type of ining regulated by the law. Two major goals of the law are: (1) to imit adverse environmental impacts of present surface mining and 2) to aid in the rehabilitation of lands that have already been dversely affected by coal mining in the past. (The law is discussed n greater detail in Chapter 7.)

In the United States, the institutional means for allocating round-water resources and for resolving conflicts over their use are ased upon a system of private property rights, market exchange, and pplemental government regulation to correct perceived market ailures. In that respect, ground water is treated no differently in inciple from other resources, goods, and services. However, because f the changeable characteristics of the ground-water resource, merican institutions approach the allocation of ground water less ffectively than they do the allocation of most other goods and ervices. Consequently, conflicts over the use of ground-water sources are not always effectively or equitably resolved, and more ubstantial problems can be anticipated in the future.

GROUND-WATER PROBLEMS--THE INSTITUTIONAL ISSUES

Ground-water resources are now being depleted in some parts of the nited States. The High Plains of Texas, Oklahoma, and states to their orth, and the Central Valley of California are regions of major oncern. In those areas, pumping of ground water for irrigation is

economical, and activities dependent on it have been curtailed not only results in economic loss and social disruption for wa (primarily farmers), but it threatens to destroy the economic entire communities and regions. Ground-water mining and its i economic consequences are not necessarily bad. Not to mine a ground-water resource may mean to forego economic activity whi if temporary, may add substantially to the nation's productivi the very least, however, the inevitable resource depletion and associated economic decline should be anticipated and managed so that the human and economic costs are minimized. Unfortuna existing ground-water allocation institutions are usually inac tools for achieving such rational resource management.

Ground-water laws in most states permit landowners to expl resource at rates which do not manage the resource economicall Indeed, as water tables fall, landowners are motivated to use water even more rapidly in order to get as much of it as possi before the costs of doing so rise higher, as they inevitably w

Many other ground-water problems are caused, or at least inadequately dealt with, by existing institutions. However, i important to analyze the reasons why such problems occur and p than it is to describe them at length.

In the United States, conflicts over the use of scarce res are predominantly resolved by our system of private property r market exchange. In this system, those who need the resources control by purchasing user rights. This approach dispenses wi need for centralized control by creating incentives for indivi act in the best interests of the entire society without coerci mandates. The system can, however, be distorted and fail to f in the best interests of all of its members. Moreover, charac of the ground-water resource itself give rise to two sources o failure, which merit discussion here.

Water, whether in the ground, on the earth's surface, or i atmosphere, is a transient resource. Because of its physical the resource is mobile and difficult to reduce to possession. water use in one place is likely to affect water use in other by altering the quantity, quality, or timing of resource avail But because water is a transient resource, property rights to difficult to define. They can usually be defined only as righ divert or pump at a particular rate, and not as rights to this specific and identifiable unit of water.

Unless water rights can be defined, they cannot be bought sold. The absence of property rights creates what economists externalities, which are activities that are not priced and ar undervalued by the market system. In this instance, the fugit nature of water helps to create spatial externalities which, i lead to inappropriate water use. For example, ground-water pu lower water tables and impose costs on other water users. How is difficult to define the rights of those other users in such to permit market institutions to encourage the proper rate of by each user. Spatial externalities, due in part to the fugit

ground-water recharge often occurs slowly as well. Therefore, changes in ground-water resources may persist for a long time. Effects of current ground-water mining or ground-water quality degradation may be felt by future generations even more than by present ones. The market system, however, pays little heed to the welfare of future generations. The unborn possess no property rights and cannot signal their preferences through current market transactions. This need not be important when current water uses produce few lasting or long-term consequences, as in the case of recreation and other nonconsumptive water uses. However, consumptive or polluting uses, especially those of ground-water resources, do produce long-term consequences that are undervalued and inadequately recognized by a market system. Ground-water contamination is controlled, if at all, by federal and state water quality (and surface-mining) regulations.

The causes of market failure can be remedied by several means. One is to create new property rights, such as liability rules that effectively create a right of immunity from a specified externality. This right can then be bought and sold, as in the case of an easement. Economic incentives can be used to encourage the creators of externalities to modify their actions and reduce the costs they impose upon others. Most commonly in our society, government regulation can be used to limit the imposition of external costs. At the extreme, government can assume control through public ownership of the resources themselves, thus acting directly to limit the production of externalities.

In the case of ground-water resources, specifically with respect to degradation of ground-water quality, both liability rules and government regulations to control externalities are being employed. In each case, application is somewhat uncertain because the necessary information is lacking either to define property rights clearly or to set standards and enforce regulations.

In general, institutions for controlling ground-water use in the United States have not evolved to the point where existing and future conflicts can be adequately resolved. Ground-water withdrawals are governed almost entirely by state water laws, which allocate rights primarily to owners of the overlying land. The laws make owners liable for damages to other water users to a limited extent but often fail to recognize the close relationship between surface water and ground water.

GROUND-WATER MANAGEMENT

Since the 1950s, a growing proportion of the population has begun to voice concern that national development is taking place at the expense of environmental quality and public health. Recent federal

legislation that attempts to achieve a better balance of e
environmental interests, especially in the area of water q
protection, includes the following acts: the National En
Protection Act, the Coastal Zone Management Act, the Safe
Water Act, the Resources Recovery and Conservation Act, th
Mining Act, and the Clean Water Act. Although some of th
more explicit than others regarding ground water, they ar
concern at the federal level for managing both ground wat
water. Traditionally, however, ground-water management a
has been a state and local responsibility, because of the
nature of the ground-water resource and its use.

Water resource managers whether on the state or feder
frequently overlooked ground water as an integral element
systems. Extensive alteration in the supply or quality o
water, especially in conjunction with limited surface sup
lead to severe economic or other social disruptions that
alleviated by resources at the state or local levels. On
hand, ground water appropriately managed is an important
drought-resisting component in the total water supply. M
disruptions can be averted by using stored ground water a
for surface water during a drought period (Bennett 1979).
because changes in the natural regime of surface water o
generally affect each other, it is appropriate to treat t
resources.

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CHAPTER 3

COAL MINING IN THE UNITED STATES

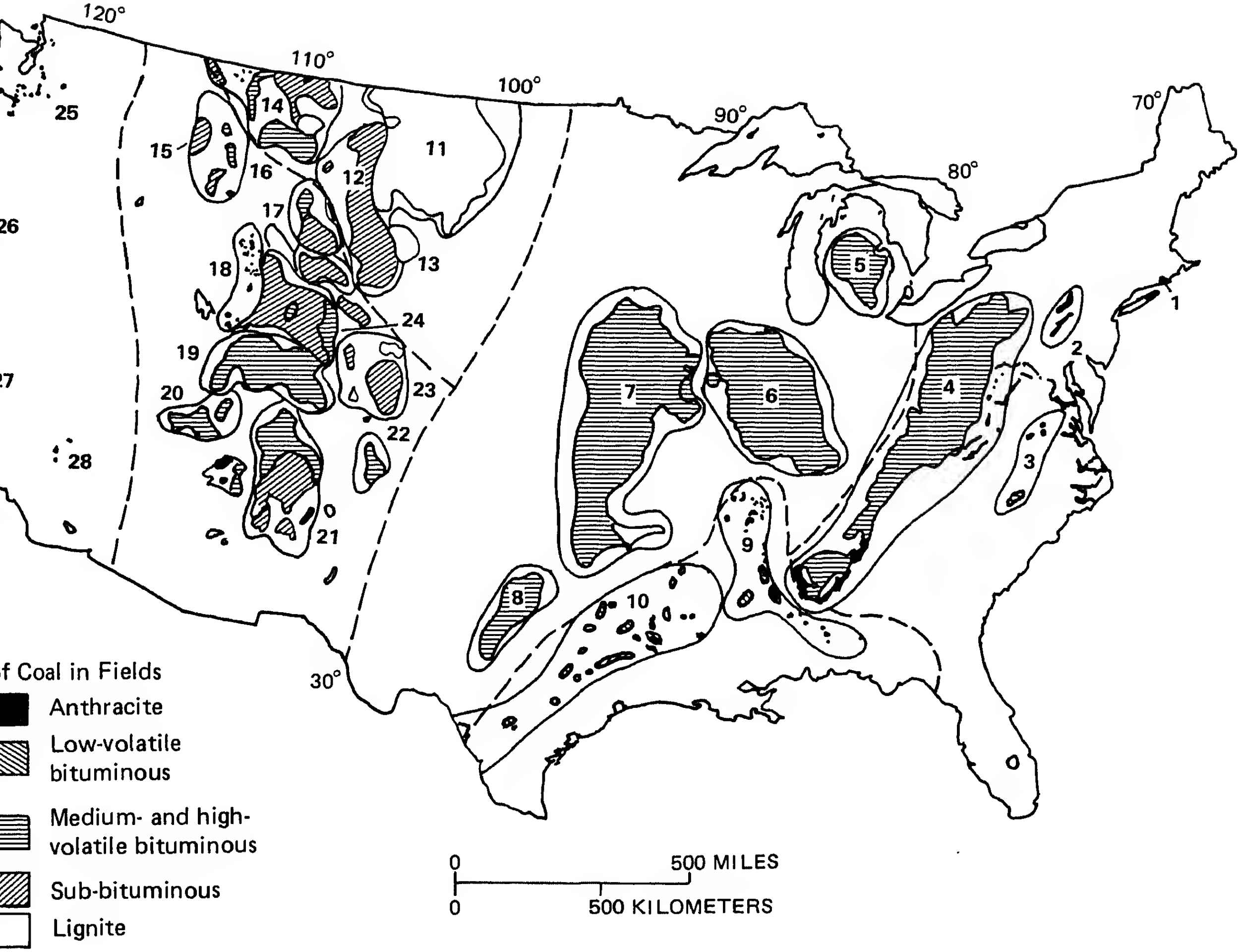
INTRODUCTION

In the previous chapter, general aspects of the ground-wa resource in the United States were discussed. In this chapte discussed: what it is, where it can be found, how it is mine the hydrogeologic conditions are within major eastern coal ba western coal provinces. The information will serve as backg later discussions of the relationship between coal mining and ground-water resource.

The 100th meridian was chosen as the boundary between Eas for the purposes of this report. The distinctions between de of coal basins (eastern United States) and coal provinces (we United States) were made on the basis of geologic variations availability. Geologic conditions in the western region are uniform: coal occurs in younger rocks that are less deformed areally extensive. Site-specific hydrogeologic studies in co may be more common in the West, whereas regional hydrogeologi on a basin-by-basin level, are more common in the East.

COAL RESOURCES IN THE UNITED STATES

Coal reserves in the conterminous United States have been into 6 coal provinces and 24 coal regions on the basis of phy and geologic similarities (Figure 3.1). Total recoverable re coal are almost evenly divided between East and West. (Recov reserves are deposits that are assumed to be commercially min virtue of seam thickness and accessibility and under known technological and legal constraints; the definition excludes underground coal gasification.) The distribution and product recoverable reserves (as of January 1, 1976) in the East and summarized in Table 3.1. On a tonnage basis, 53 percent of t recoverable reserves are found in the West. A projection of production, based on 1977 production figures (Table 3.2) and anticipated incre d emand for coal, indicates that coal pr



Provinces

Eastern
- 1 Rhode Island meta-anthracite
- 2 Pennsylvania anthracite
- 3 Atlantic coast
- 4 Appalachian

Interior
- 5 Northern
- 6 Eastern
- 7 Western
- 8 Southwestern

Gulf
- 9 Mississippi
- 10 Texas

ern Great Plains
- 11 Fort Union
- 12 Powder River
- 13 Black Hills
- 14 North Central

Rocky Mountain
- 15 Tertiary lake beds
- 16 Bighorn Basin
- 17 Wind River
- 18 Hams Fork
- 19 Uinta
- 20 Southwestern Utah
- 21 San Juan River
- 22 Raton Mesa
- 23 Denver
- 24 Green River

25-28 Pacific Coast Province

TABLE 3.1

Distribution of Coal Reserves and Production in million tons (as of Ja

State	Recoverable Reserves			1975 Produ	
	Under-ground	Surface	Total	Under-ground	Surface
EASTERN U.S.					
Ohio	7,500	4,900	12,400	16.2	29.3
Pennsylvania	16,700	1,200	17,900	43.8	39.9
Kentucky (eastern)	5,200	3,600	8,800	41.5	48.0
Virginia	2,000	700	2,700	24.0	12.8
W. Virginia	19,100	4,100	23,200	88.4	20.5
Maryland	500	100	600	0.2	2.5
Alabama	1,000	1,100	2,100	7.4	14.2
Tennessee	400	300	700	4.1	4.7
Illinois	30,300	12,700	43,000	31.0	27.0
Indiana	5,100	1,400	6,500	0.4	23.7
Kentucky (western)	4,800	3,200	8,000	22.5	28.3
Arkansas	100	100	200	-	0.6
Iowa	1,000	400	1,400	0.3	0.5
Kansas	-	800	800	-	-
Missouri	800	2,900	3,700	-	5.4
Oklahoma	700	300	1,000	-	3.3
Texas	-	2,500	2,500	-	14.2
WESTERN U.S.					
Montana	40,400	39,700	80,100	-	26.1
N. Dakota	-	8,100	8,100	-	11.1
Wyoming	18,000	19,000	37,000	0.6	30.3
S. Dakota	-	300	300	-	-
Colorado	7,100	3,000	10,100	3.4	6.1
Utah	3,600	200	3,800	7.9	-
Arizona	-	300	300	-	10.2
N. Mexico	1,200	2,000	3,200	0.9	8.9
Washington	600	400	1,000	-	3.9
Alaska	3,100	600	3,700	-	0.7
TOTAL	169,200	113,900	283,100	292.6	367.3

SOURCE: Modified from Office of Technology Assessment (1979)

LE 3.2

jection of coal production in millions of tons

	Year		
	1977	1985	2000
SURFACE MINES			
East	276	205-250	225-310
West	141	415-495	700-1,005
Total	417	620-745	925-1,315
UNDERGROUND MINES			
East	259	285-340	500-685
West	13	50-60	80-110
Total	272	335-400	580-795
TOTAL			
East	535	490-590	725-995
West	154	460-555	780-1,115
Grand Total	689	955-1,145	1,505-2,110

RCE: Modified from Office of Technology Assessment (1979)

may more than double by the year 2000. Based on these projections, surface mines will supply the majority of the resource, and the weste coal producers will be major suppliers of the nation's coal. Underground production is expected to double also, with the majority underground coal being produced from eastern provinces.

MINING METHODS

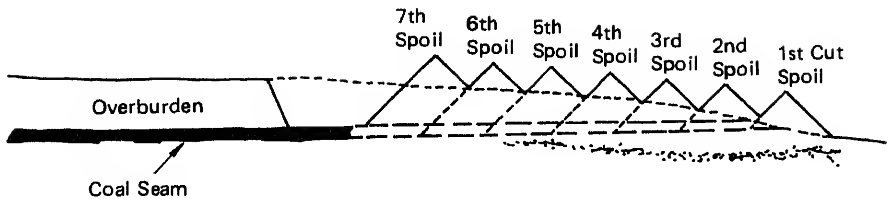
To understand the effect of coal-mining operations on the ground-water resource, each of the current mining methods is reviewed below. The principal methods currently used in the United States are surface mining and underground mining, both of which include a number of variations. Site facilities (mine offices, maintenance and shippi facilities, processing plants, waste storage areas, sediment control ponds, and haul roads) are also taken into account when evaluating th effect of a mining method. Coal processing and waste storage areas that are not isolated from the hydrologic systems also may contribute to the overall effect that a specific mine operation will have on the hydrogeologic system.

Surface Mining

Of all mining methods, surface mining physically disrupts the largest amount of geologic materials because it requires the excavati of soil and other material that overlies the coal. (The material overlying the coal is referred to as "overburden," and the fractured, unconsolidated overburden excavated by the mining process is referred to as "mine spoil.") Area, contour, open pit, mountaintop removal, a auger methods are five variations of surface mining. The selection o any of these methods is dependent on the economics of removing the overburden to recover the coal, available mine engineering and equipment, and local topography.

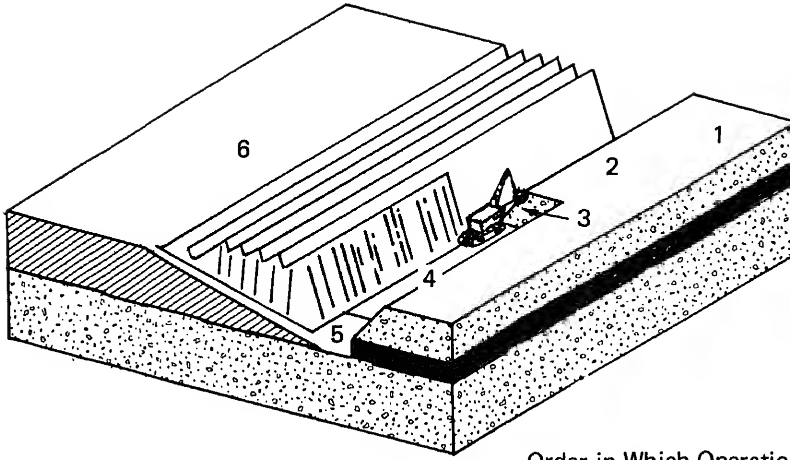
Area Mining

The area-mining method is used in gently rolling to near level terrain. Draglines, shovels, or wheel excavators are used to remove the overburden and expose the coal. The coal is removed and a second phase of overburden removal is undertaken. The spoil from the second cut is deposited in the area from which the coal was previously mined (Figure 3.2 and 3.3). Area mining continues into thicker overburden areas until either property boundaries, the physical or economic limi of the equipment, or another outcrop is reached. The excavation of t sequence of cuts may extend for several thousand feet.



SOURCE: U.S. Department of the Interior, 1978.

FIGURE 3.2 Typical Cross-Section of an Area Surface Mining Operation



Order in Which Operatio
are Performed:

1 Topsoil Removal
2 Overburden Drilling
and Blasting
3 Overburden Removal
4 Coal Drilling and
Blasting
5 Coal Loading and
Hauling
6 Reclamation

SOURCE: U.S. Department of the Interior, 1978.

FIGURE 3.3 Area Mining Using Draglines (Hypothetical pit arra

Contour mining is used in mountainous and hilly terrain. As the mining operation penetrates the hillside, overburden thickness increases until the ratio of overburden to seam thickness becomes too large. In the past, spoil has been placed downhill but recent regulations require refilling the mined area. (See Figure 3.4.)

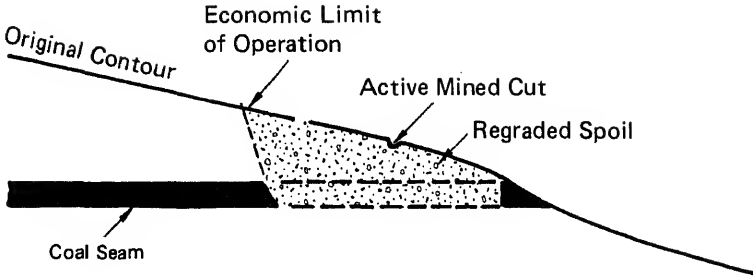
Because of recent coal mining regulations, block-cut mining is becoming an increasingly popular variation of contour mining under moderate to steep slope conditions, especially in the Appalachian region. The cuts are mined as units, thereby making it easier to retain the original slope and shape of the mountain. The cuts reduce spoil spillage on the outslopes and create few environmental disturbances. All spoil, except for the initial cut, is moved laterally along the bench (Figures 3.5 and 3.6).

Initially, a box or block cut is excavated as close to the center of the mining permit area as possible. Coal from this initial cut is removed, after which overburden from the second cut is placed in the first cut. When the coal from the second cut is exposed and ready for loading, stripping of the third cut begins and continues through the loading of the coal from the second cut, placing the spoil in the remaining portion of the initial cut. Successive cuts become smaller as mining continues, thus minimizing the amount of overburden that must be hauled to fill the final pit.

Another variation of the contour-mining method utilized today is mountaintop removal. In this operation, the ratio of overburden to coal-seam thickness is such that a whole hilltop can be removed. In this situation, a combination of contour and area mining methods is used. In some cases, overburden is hauled over the side of the mountain to fill the heads of valleys adjacent to the mine, a technique called head-of-hollow fill; however, recent regulations require refilling the mined area with spoil. The mountaintop-removal method reduces the normal slope at the top of the mountain to a relatively flat surface (Figure 3.6).

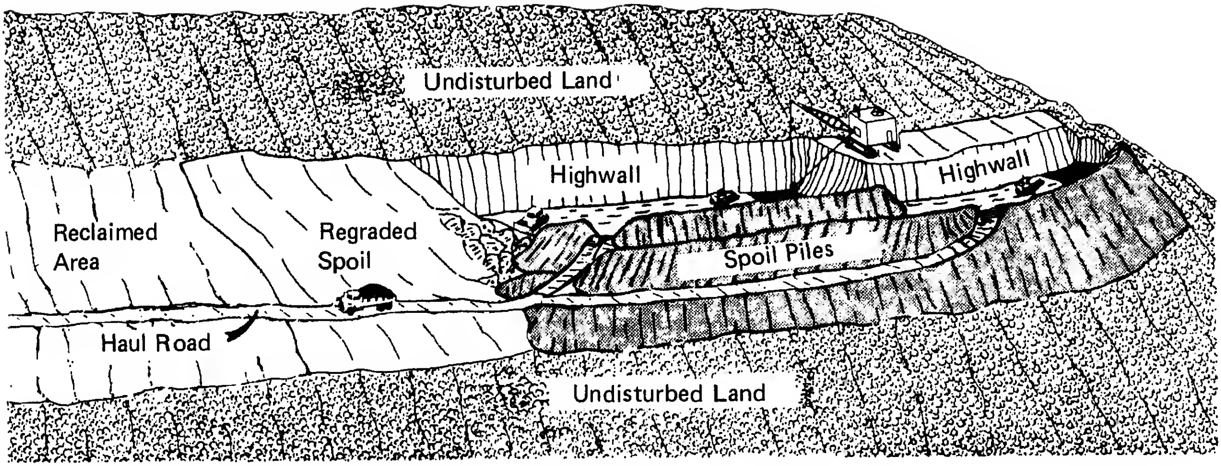
Auger Mining

Another mining method related to contour mining is auger mining. When the economic limit is reached by using other surface-mining techniques, the remaining coal seam exposed at the bottom of the final highwall can be extracted by other methods. The remaining coal can be practically recovered by conventional underground drift mining, by punch mining (a limited drift mine), or by auger mining. Augers often can remove coal that is physically or economically impossible to recover by any other means. Penetration is usually less than 200 ft., and spacing of the auger holes, which is a function of the coal strength, can be from a few inches to 2 or 3 ft.



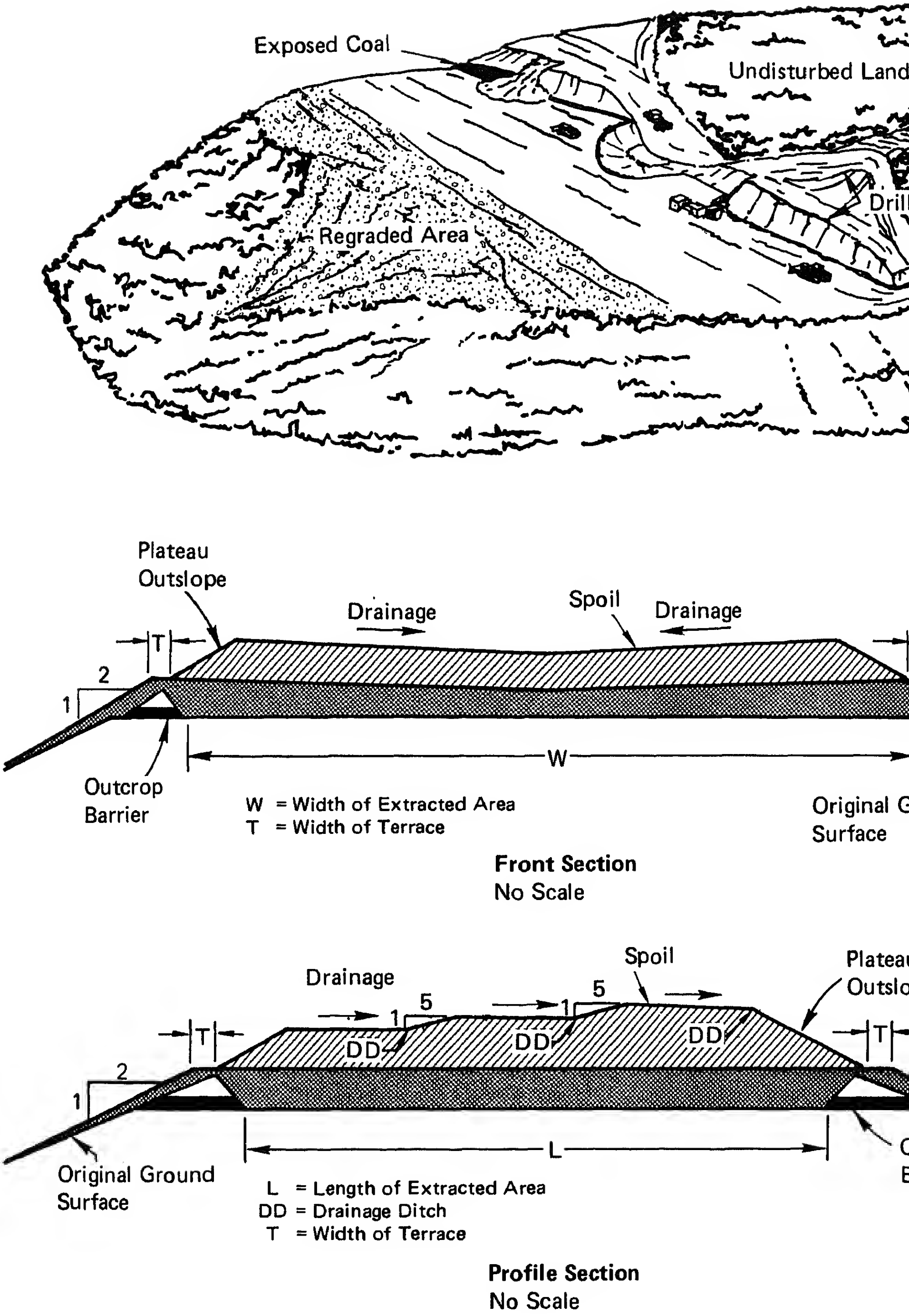
SOURCE: U.S. Department of the Interior, 1978.

FIGURE 3.4 Cross-Section of a Contour Mining Operation



SOURCE: U.S. Bureau of Mines, 1975.

FIGURE 3.5 Typical Block-Cut Contour Mining Method



SOURCE: U.S. Department of Energy, 1979.

FIGURE 3.6 Schematic and Cross-Section of Surface Mining Mountaintop Remova

n-Pit Mining

The conditions for this type of mining are similar to those of a quarry operation in that the thickness of the seam is much larger n that of the overburden (i.e., the ratio of overburden to seam kness is very low). When such extremely thick seams of coal are oved, the entire mined area cannot be completely refilled with the burden materials removed from the pit. As a result, a depression somehow different topography remains when the site is abandoned.

Underground Mining

Underground mining has wide-ranging effects on the geology of a area. The principal disruption of the geologic setting is the oval of all or a portion of the coal seam. However, entryways, air ts, and various mining methods can also cause roof collapse, which result in surface subsidence.

Underground mining uses three types of mine entries: drift, slope, shaft. Within each of these designs, two techniques for extracting erground coal may be applied: room and pillar, and longwall-twall mining. As with surface mining, the type of underground ng method utilized in a particular setting depends on mining omics, available mine engineering and equipment, and local ography of the mine site.

rground Mine Entry

For any mine, one or more types of entries may be constructed, nding on the location of the coal seam and the geology of the mine.

Drift Entry. A drift entry or drift mine is one that has a nearly zontal entry. The seam of coal outcrops at the surface in the side hill or mountain, and the opening into the mine may be made ctly into the coal seam (Figure 3.7). This type of mine is rally the easiest and cheapest to construct because no excavation ugh rock is required. Coal may be transported to the outside by n, belt conveyor, hydraulic slurry pipeline, or battery-powered er-tired equipment.

Slope Entry. A slope entry or slope mine is an inclined opening to tap the coal seam (or seams). A slope mine may follow the coal if the bed itself is inclined and outcrops, or the slope may be en through rock strata overlying the coal to reach a coal seam ure 3.8). In the past, slope mines generally have not been oyed as much as shaft mines, but with the application of -tunneling machines for slope development, slope mines are being nded to ever-deeper coal seams. Transportation of coal from a e mine can be by conveyor, hydraulic slurry pipeline, train (using

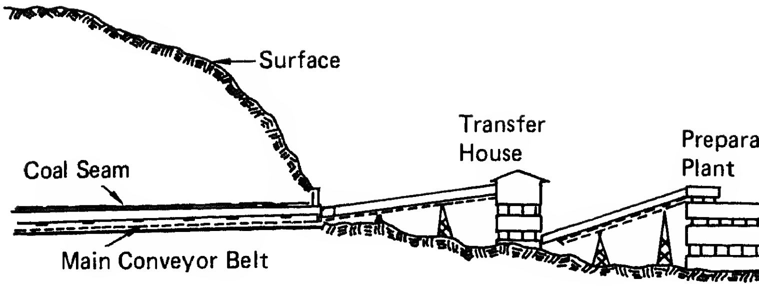
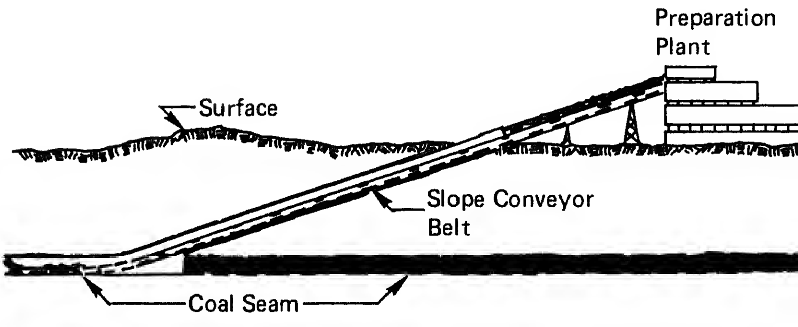


FIGURE 3.7 Diagram of a Drift Mine Entry



SOURCE: U.S. Bureau of Mines, 1975.

FIGURE 3.8 Diagram of a Slope Mine Entry

ne slope by an electric hoist and steel rope if the grade is p). The most common practice is to use a belt conveyor where es do not exceed 18 degrees.

Shaft Entry. A shaft entry or shaft mine (Figure 3.9) is a ical opening from the surface to the coal seam. Shafts are ally preferred to slope mines if the coal seam is beneath deep r, particularly given the current availability of automatic ting equipment.

rground Mining Methods

Underground mining uses either the room and pillar method for which may be left as roof supports at the completion of mining, or the wall and shortwall methods, which use temporary hydraulic supports ng extraction.

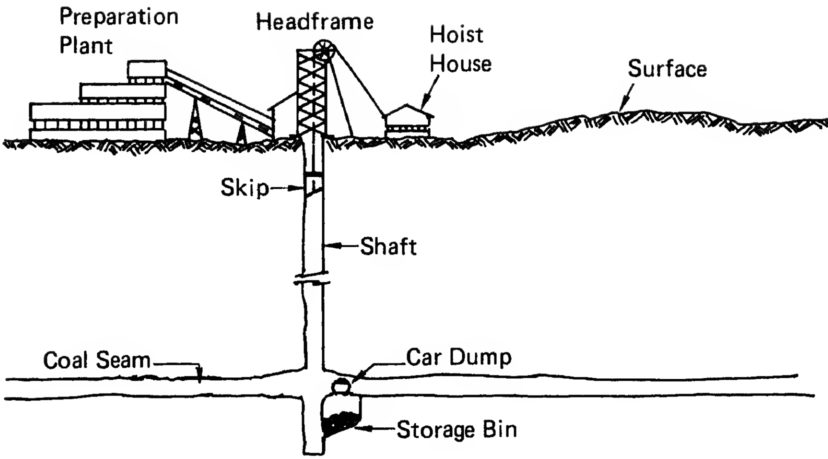
Room and Pillar. This system is the most common mining method in United States. Excavation is initiated at one location and is nced along a series of working faces by either conventional or inuous mining equipment (Figure 3.10). Many acres are mined in a and, as the mine gets older, a honeycombed network of openings is ted. One of the problems associated with this method is the rrence of land subsidence above the mined regions resulting from collapse and fracturing of the overburden. After a mined-out ion is abandoned, subsidence may occur at any time, from months to s. In retreat mining, the pillars are systematically removed after ction is mined out and roof collapse and subsidence are almost antaneous. This mining technique greatly increases the fracturing verlying material.

Longwall and Shortwall. Longwall mining and shortwall mining are lar in mining plan, differing only in equipment used to extract the . In general, a block of coal 400 to 800 ft. wide and 1,000 ft. or in length is mined by a large shearing machine. The mine roof is up by hydraulic supports that move with the cutting face. The collapses behind the operation, which results in immediate idence and fracturing of material above the seam.

Underground Coal Gasification

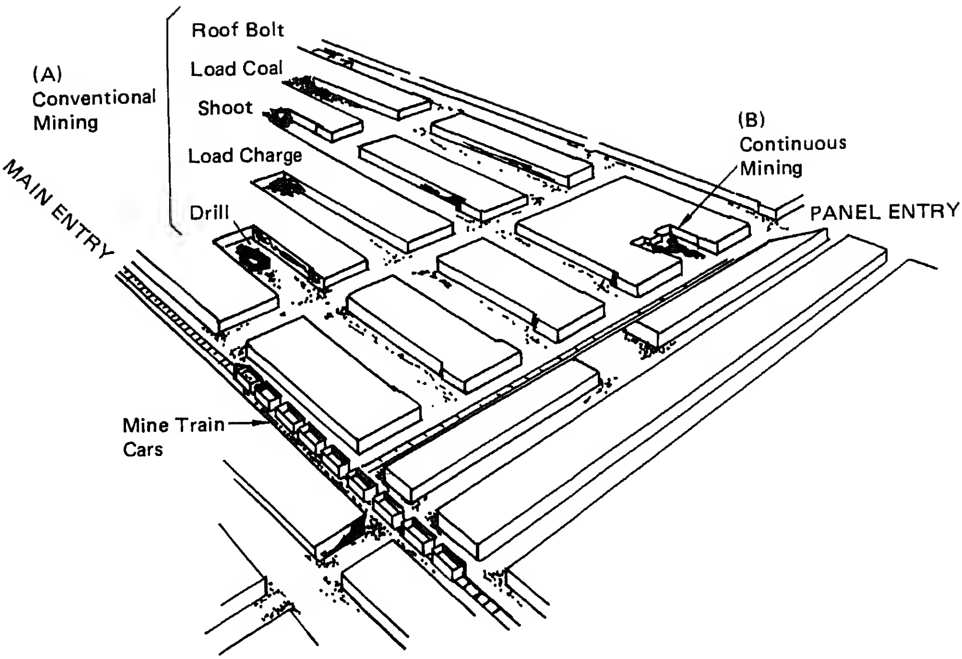
At this time, underground coal gasification activities in the ed States and Canada are experimental and consequently small-scale ations, designed to yield knowledge about the technological and ronmental aspects of the mining technique.

Coal is gasified underground (in situ) by (1) drilling boreholes



SOURCE: U.S. Bureau of Mines, Skelly and Loy, 1975.

FIGURE 3.9 Diagram of a Shaft Mine Entry



SOURCE: U.S. Department of the Interior, 1978.

FIGURE 3.10 Room and Pillar Work Faces

the gas from the production wells. The injection and pr
may be spaced 10 to 30 meters apart in an array of colur
that optimize resource recovery. The air or steam and c
forced through the seam/reaction zone by mechanical comp

The natural permeability of coal is too low to allow
rates of injected and product gases required to sustain
Thus, an extremely important part of the in-situ mining
enhance the permeability of the coal seam in the zone be
and production wells. This process, called linking, is
reverse combustion or by directional drilling.

Process Chemistry

Two distinct chemical reactions are involved in the
coal gasification process: pyrolysis and gasification.
causes exothermic reactions with coal and char and prod
carbon dioxide (CO_2) and steam (H_2O). The heat generat
gases react with char to form carbon monoxide (CO), hyd
methane (CH_4), and coal tar. Heavier components conden
in the seam, and the lighter components arise as produc
liquids that condense out of the gas stream are eventua
the areal sweep of the process expands.

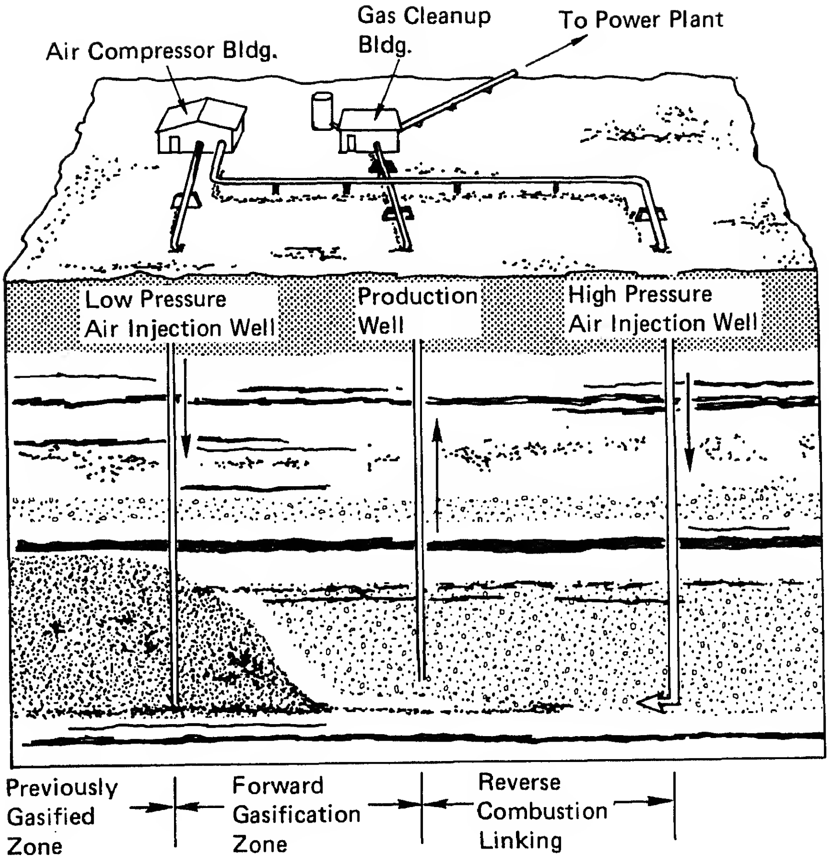
Linked Vertical Well Concept

The linked vertical well concept of underground coa
is applicable to coal seams which are nearly horizontal
by drilling vertical wells (which are cased only to the
seam) into the coal seam to provide for injection of ai
of product gases. Reverse combustion is used to link t
the coal seam, followed by forward gasification of the
linked wells.

In Figure 3.11 the center and right wells are linke
combustion. High pressure air is injected in the right
to flow to the center production well through naturally
cracks and paths in the coal. The combustion zone adva
well to the right (injection) well against the gas flow
char channel between the wells. Once two wells are lin
gasification front reverses direction moving with the g
second stage, called forward gasification, is shown bet
and center wells in the diagram. Forward gasification
the linked passage which widens and caves in to expose
1979).

Steeply Dipping Bed Concept

The steeply dipping bed (SDB) process is being deve
coal seams that dip at angles greater than about 35 deg



SOURCE: Brown, R., 1979.

FIGURE 3.11 Schematic of the "Linked Vertical Wells Concept" for Underground Coal Gasification

coal is not recoverable by existing mining methods. Dri
requirements and subsidence problems are less severe for
than for the other underground coal gasification process

As illustrated in Figure 3.12, slanted holes, cased
the overburden, are drilled into and through the coal be
dip. A channel connects the lower ends of the slanted p
wells. All injection wells are drilled either verticall
underneath the coal bed, or into the coal bed itself to
horizontal channel connecting the uncased production hol
gases are withdrawn through the slanted holes in the coa
between the injection holes. Reducing reactions occur o
of the slanted, uncased exhaust holes. As the coal alon
horizontal channel burns away, the fire zone advances up

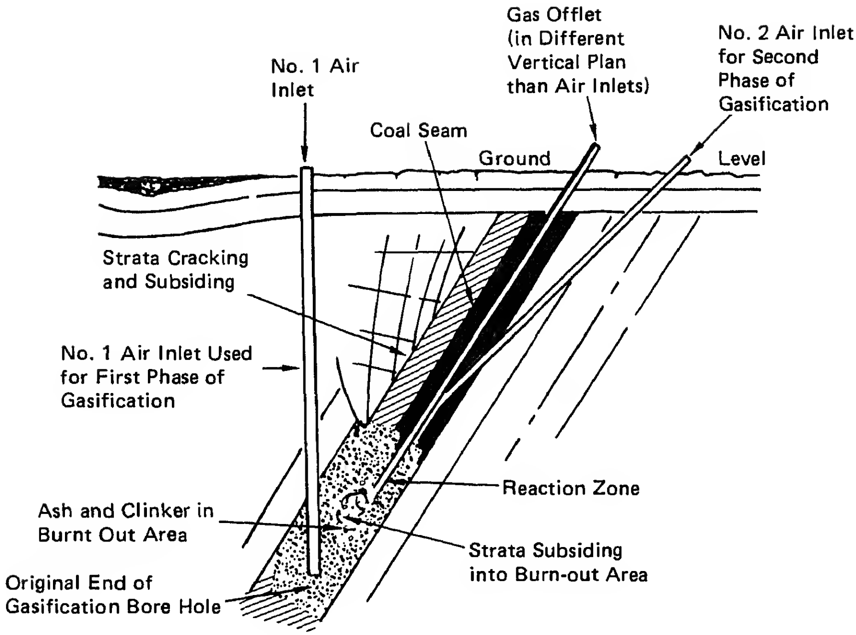
Steeply dipping beds generally are uneconomical to m
100 billion tons of SDB coal are estimated to exist in t
States. Because a large percentage of Pacific Coast coa
dipping, commercialization of an SDB process would contr
future energy supply of the West Coast. There are also
deposits in the Rocky Mountain area and lesser amounts e
100th meridian.

The underground gasification of SDB coal is under de
the Gulf Research and Development Company and TRW System
near Rawlins, Wy. The Soviet Union has been highly succ
employing slant drilling along the dip of a coal bed (Br

COAL REGIONS AND HYDROGEOLOGIC SETTINGS

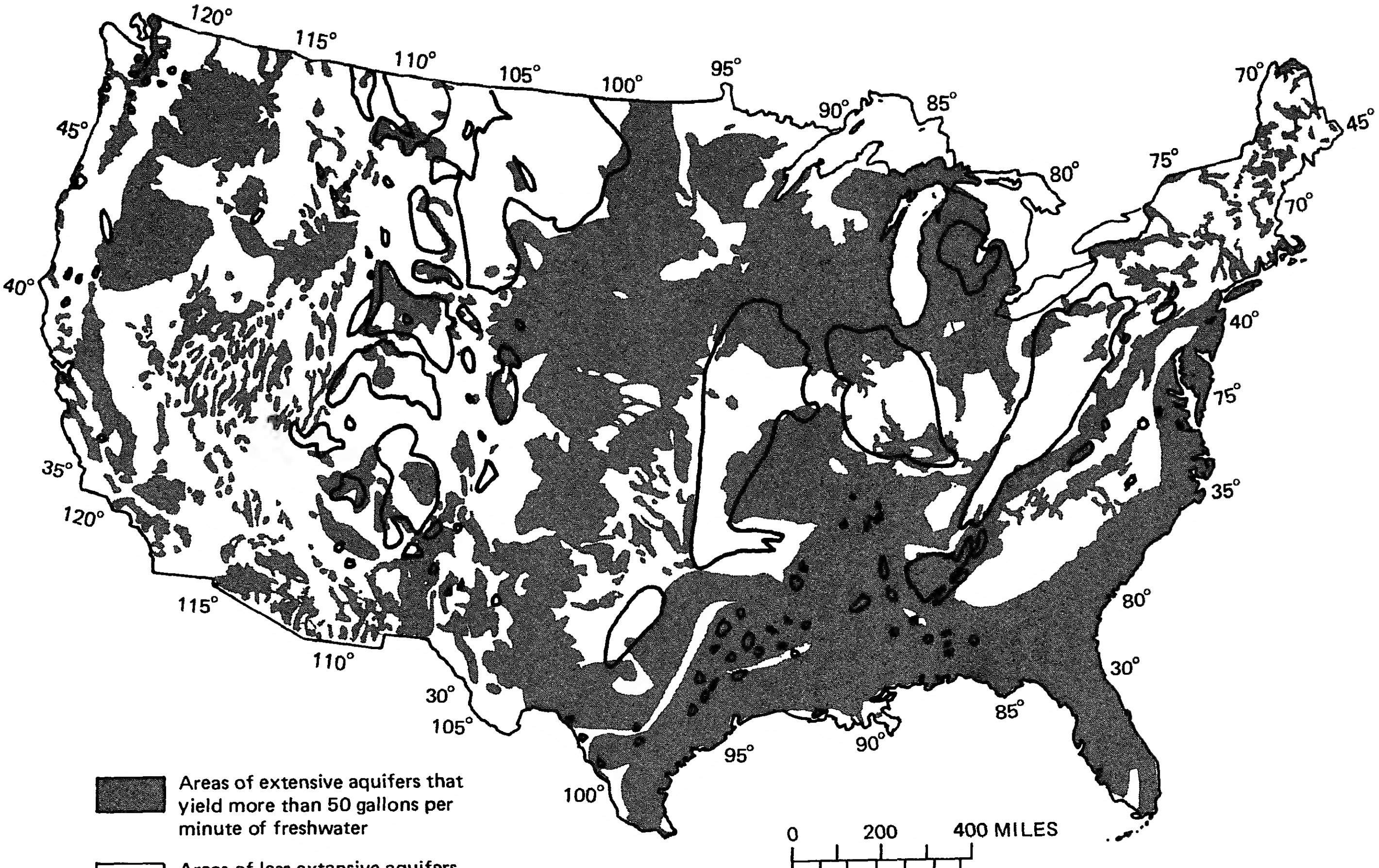
The relationship between coal-mining regions and gro
resources can be seen by combining the information on aq
Figure 2.2 with the location of the coal basins in the U
shown in Figure 3.1. Examination of the resulting figur
illustrates that most coal basins fall within the region
States where aquifer yields are generally less than 50 g
minute (gpm) and are less extensive. Exceptions are the
in northern Alabama, the Micaza coal basin, the northern
Green River basin in Wyoming, the central part of the Sa
region in northern New Mexico, and the Denver basin in C
small coal regions of the Gulf Coast Province also occur
extensive aquifers that produce 50 gpm are present.

Coal mining in the eastern United States, in progres
18th century, has been conducted in all types of geologi
hydrologic settings and at varying scales. Large-scale
western United States is relatively new, beginning in th
20th century. Because of the long history of mining and
hydrogeologic settings found in the East, the following
eastern coal mining and its hydrogeologic settings is fo
provinces and coal basins. For the West, the discussion
provinces only, because of the relatively recent occurre
large-scale mining there and the lack of detailed mining
hydrogeologic data for number of the western coal basi



SOURCE: U.S. Department of Energy, 1979b.

FIGURE 3.12 Schematic of "Steeply Dipping Bed Concept" for Underground Coal Gasification


120°
115°
110°
105°
100°
95°
90°
85°
80°
75°
70°
45°
40°
35°
30°
0
200
400 MILES
Areas of extensive aquifers that yield more than 50 gallons per minute of freshwater

Eastern United States

oal resources of the eastern United States are found in three coal nces: the Eastern Province, the Interior Province, and the Gulf nce. In these provinces, the coal seams range from horizontal to ly dipping and complexly folded and faulted beds; many seams ally are 2 to 3 ft. thick but can range up to 10 ft. or more. The that have been mined most extensively are at or near land ce. Before World War II, eastern coal was primarily extracted by ground methods, but subsequent development of large earth-moving ment has made surface mining a more attractive alternative in years. Surface-mining production currently surpasses ground output. Mining methods now employed include underground, ur, area stripping, mountaintop removal, and augering.
he climate of the eastern United States is generally humid, and pitation averages from 30 to 40 in. annually. The topography s from coastal plains to the Appalachian mountains. The tions in the geologic and hydrologic settings of the coal rces of the East are discussed below by coal province and related basins.

rn Province

he areas included in the Eastern Province are shown on Figure 3.1 ons 1 through 4). Reserves in the regions total about 112 billion and are evenly distributed between the Northern and Southern achians Regions. About 92 percent of the coal in the area is in Virginia, Pennsylvania, Ohio, and eastern Kentucky; in 1976, those s provided about 82 percent of the total production in the Eastern nce. West Virginia, eastern Kentucky, and Virginia contain ficant reserves of low-sulfur coal. Furthermore, methane gas, is associated with coal deposits, is an important source of y in the Appalachians. Underground mining in the province ts for the largest production; in 1975, 56 percent of the coal from underground mines. Only about 15 percent and 20 percent of eserve base can be removed by surface mining in the Northern and ern Appalachians, respectively.
or the purposes of the report, the Eastern Province has been ed into the Northern Appalachian Coal Region, Central Appalachian Region, Southern Appalachian Coal Region, Pennsylvania Anthracite n, Atlantic Coast Triassic Coal Region, and Narragansett Coal , each of which is discussed in detail below.

orthern Appalachian Coal Region. The Northern Appalachian Coal n covers 53,000 sq. miles in 94 counties of Pennyslvania, Ohio, Virginia, and Maryland. Physiographically, the region lies within ppalachian Plateau Province and portions of the Valley and Ridge ce. The area is characterized by a glaciated section of gently

mountainous section of considerable relief ranging from 500

The annual precipitation averages between 38 in. and 50
June, and July are the wettest months. Potential evapotrans
26 to 30 in. annually. The average annual temperatures are
58°F, the minimum January temperatures are 20°F to 30°F, an
maximum July temperatures are higher than 70°F.

The coal-bearing formations of this region are Pennsylv
age. The Pennsylvanian-aged sequence has been separated in
formations (in ascending age order): Pottsville, Allegheny
and Monongahela. Conglomerates, sandstones, shales, limest
coal seams are characteristic of the formations. The Potts
formation crops out around the periphery of the region and
contains as much as 80 percent sandstone. The Allegheny F
tends to be composed of fine-grained material in the northe
the region and becomes coarser sandstone and conglomerate t
south. The Conemaugh Formation is composed of 50 to 80 per
fine-grained mudstone and lacks significant coal seams. Th
Monongahela Formation consists of cyclic rock sequences tha
more limestone than the lower formations.

The occurrence of ground water in the consolidated rock
Northern Appalachian Region depends on the environment of d
and subsequent fracturing of geological materials and topog
These factors have resulted in the general lack of regional
and usable ground water above stream level. However, water
quality is found within the Allegheny and Conemaugh formati
often of sufficient quantity to be an important source of w
Throughout the region, the most common occurrence of ground
joints and fissures in the rock (secondary permeability).
particularly near the tops of anticlines, tend to be open n
surface but closed at depth. The environment of deposition
impact on the present ground-water conditions in the region
Underclays commonly found beneath the coal seams and indura
siltstones and claystones tend to reduce or negate downward
of water. Where these rock types are present, many zones c
water tables have resulted. When perched zones discharge c
hillsides, springs usually form.

The sandstones of the Pottsville Formation are known to
producers of water and cover a large enough area to be of r
importance. In descending order, the sandstones are the Ho
Connoquenessing, and the Burgoon. The ability of the sands
yield water to wells varies. Yields of 50 to 200 gpm have
reported from wells completed in the Burgoon. Glacial mate
wide range of hydraulic conductivity: clay tills often hav
low hydraulic conductivities, while other glacial materials
sands and gravels can yield large amounts of water.

Although excellent water-producing areas are known, lat
in the rock have limited the areal extent of their importan
limiting factor, particularly for the Burgoon Sandstone, is
tendency for salinity to increase with depth. The Homewood
Connoquenessing sandstones are often productive water-beari
however, the water

is of poor quality, containing high concentrations of iron and, sometimes, hydrogen sulfide. Mining operations in the Allegheny and Pottsville formations have encountered significant amounts of water. Some underground mines routinely pump more than 1 million gallons per day from relatively small acreages. The level of discharge has a significant effect on the quantity of water available within the vicinity of the mine.

Central Appalachian Coal Region. The Central Appalachian Coal Region covers 35,000 sq. miles in 70 counties of West Virginia, Kentucky, Tennessee, and Virginia. The eastern section of the region is in the western edge of the Valley and Ridge Province, while the major portion lies in the Appalachian Plateau Province. A portion of the region is affected by the structural deformation that resulted in the Appalachian Mountains; in this area, relief may be in excess of 1,000 ft. Elsewhere, the more gently rolling topography decreases to the west. Much of the area can be described as low hills with steep valley walls and a dendritic drainage pattern.

The region has a moderate climate with mild, damp winters and hot, humid summers. The mean annual temperatures are 56°F to 58°F. Temperatures range from in excess of 90°F in summer to below freezing during the winter. The annual precipitation is about 45 in. Some sheltered valleys receive as little as 40 in., while portions of Tennessee in the higher elevations receive in excess of 55 in. Precipitation is predominantly in the form of rainfall, although snow does occur during winter, especially in the higher elevations. The maximum precipitation is received in late winter and early spring, and the least rainfall normally occurs during the fall.

Pennsylvanian-aged rocks average 2,800 ft. in thickness in the Central Appalachian Coal Region. Sandstones, shales, limestones, conglomerates, and beds of coal are characteristic of the deposits. The thickest section is found in southern West Virginia along the Virginia-Kentucky border. Sandstones are predominant near the maximum basin depths, while mudstones increase in thickness to the northeast and west. The younger Pennsylvanian-age sequences also become progressively finer grained and contain a greater proportion of mudstone.

The mineable coals in the Central Appalachian Coal Region are found within the Pottsville Group, the Allegheny Formation, and the Conemaugh Group. The Conemaugh consists mostly of shale, sandstone, nonmarine limestone, and minor amounts of coal. The Allegheny Formation is composed of sandstone, shale, and lesser amounts of clay, coal, and limestone. The Pottsville Group consists of sandstone with shale, numerous coal seams, and lesser amounts of clay and limestone. In Kentucky, there are 10 major coal seams; in Tennessee, there are 17, and in Virginia, approximately 27. In West Virginia, 17 coal seams account for more than 90 percent of the production, although as many as 117 seams have been named.

Ground water in the Central Appalachian Region can often be found in carbonates and sandstones. Changes in composition are very common i th r cks, and of en abrupt. The changes restrict the movemen of

ground water and result in localized water bearing zones (a
regional aquifers). Well yields can range from only a few g
minute to more than 100 gpm. In the eastern part of the reg
of the ground water is from secondary permeability (faults a
or from older geologic units below the Pennsylvanian-age roc
some areas, the Pennsylvanian rocks near the base of the mou
recharged by ground water flowing downward from older geolog
that have been uplifted to higher topographic positions.

Springs and shallow wells on the slopes of hills and inc
volumes of water in the valleys support domestic supplies.
Unconsolidated Quaternary sediments are found within the val
major streams and their tributaries. Some valley wells, esp
the alluvial deposits, support municipal and small industria
supplies. Iron and sulfates are often found in high concent
the ground water may be acidic. In the western portions of
saltwater is often encountered at shallow depths.

Most of the central portion of the Appalachian basin is
northwestward to the Ohio River, but the southern part of Vi
Tennessee drain southwestward into Alabama. These streams h
total dissolved solids and suspended solids than streams dra
where mining does not occur.

<u>Southern Appalachian Coal Region</u>. The Southern Appalach
Region covers 23,000 sq. miles in 39 counties of Tennessee,
and Alabama. It extends from a line between Birmingham, Ala
Chattanooga, Tenn. northwestward through northern Alabama an
Mississippi. The region is in the most southern extension o
flat-lying and slightly folded Cumberland Plateau Physiograp
Province. It is bordered on the southeast by the intensely
faulted Valley and Ridge Provinces of the Appalachian mounta
and on the south and west by the flat-lying younger sediment
Coastal Plain Physiographic Province.

The climate of the Southern Appalachian Coal Region is a
a large extent by maritime air masses from the Gulf of Mexic
are mild and wet, while the summers are hot and humid. The
temperature reaches 60°F to 65°F, and precipitation averages
in. annually. The maximum precipitation is received in late
early spring and almost always occurs as rain. The average
the region is 21 in. per year. Evaporation is approximately
in. per year.

The Carboniferous sediments in the Southern Appalachian
account for the greatest thickness of detrital rocks in the
occur as a wedge-shaped deposit which thins rapidly from the
the north. The Upper Mississippian Parkwood formation consi
interbedded siltstones and graywacke sandstones that contain
thin coal beds. In some instances, the coals are mineable.
Pottsville formation of Pennsylvanian age is the main coal-b
formation of the region. At the base, it consists of thick
and thinner shale units. Above this sequence is a group of
shales that have some thin coal beds. The coal seams genera
important from an economic standpoint. The upper Pottsville
contains numerous thick coal beds which are extensively

beds of one basin cannot be accurately correlated with those of r basins in the region because of the great thickening of beds to south and southeast. The discovery of new beds in the sequence and ral changes in the lithology of individual stratigraphic units ther make correlation very difficult. The region is a complex ture trending northeast-northwest.

n the Southern Appalachian Region, aquifers are present in the or limestone, the Pennington formation of the Mississippian age, the Pottsville formation. In the lowlands, Mississippian units are only exposed. The porosity of the units results from fracture and tion cavities in the limestones and dolomites. Wells successfully aced to intersect the cavities yield up to 1,000 gpm. The water in units is normally hard and, in some areas, has a hydrogen sulfide . In the uplands, wells producing as much as 450 gpm have been led in the Pottsville Formation. Normally, however, the Pottsville lies only about 5 gpm, and a few developed wells receive from 50 to pm. Ground water occurs in the sandstones and in solution ties in the carbonate units of the Pottsville. The alternating rs of permeable and impermeable rocks limit the vertical movement ater and restrict flow to intrabed avenues. The ground water in sandstone units is soft to hard, low in dissolved solids, high in , and generally corrosive.

ennsylvania Anthracite Region. The Pennsylvania Anthracite Region estricted to an area of less than 500 sq. miles in the northeastern ion of Pennsylvania where it includes parts of 10 counties. The n is part of the Valley and Ridge, and Appalachian Highlands iographic Provinces.

Prevailing winds from the west create a continental climate that is fied locally by the high ridges. Average temperatures range from of 25°F to 30°F in January, to highs of 70°F to 75°F in July. ipitation averages 42 in. per year, varying from 37 to 47 in. otranspiration is in the range of 26 to 30 in. per year.

The region is structurally composed of four synclinal basins rated by faulted and folded regions. The rocks of the sylvanian Anthracite Region consist of belts of folded shale, stone, gravel, conglomerate, and anthracite.

The anthracite-bearing rocks in the region belong to the Pottsville Llewellyn Formations. The Pottsville thickens to the southwest 225 ft. in the northern basin to 1,200 ft. in the southern basin. e are 10 thick beds of anthracite in the Pottsville Formation. The beds of the Llewellyn Formation are separated by as much as 200 of strata consisting of sandstone, conglomerate, shale, black onaceous shale, and fire clay. At least 40 important beds of racite are in the Llewellyn; the 10 thickest and most persistent r in the lower portion of the formation. The Llewellyn is about ft. thick in all but the southern basin where it is twice as k. In the northern area, the buried valley of the Susquehanna er, a former glacial stream, has cut out large areas of the upper beds.

Wells completed in the rocks yield trace amounts of wate
much as 1,000 gpm, but average only about 10 gpm. Glacial d
mantles the uplands but is generally unimportant as an aquif
Glacial outwash in the Delaware and lower Susquehanna River
however, yields moderate to very large supplies of water (up
thousand gallons per minute). The best aquifers in the anth
fields have been widely contaminated by past mining activity
Dewatering of the mines commonly leads to the draining of ro
the mine. In some locations where the rocks are permeable,
has extended laterally for several miles from the mine. Sur
streams also often leak into the underground mine workings.
Water-flooding problems have plagued most of the mining oper
water has been the direct cause of a number of mine shutdown
mines have closed, new water pools have formed underground,
levels of existing pools have risen.

Atlantic Coast Triassic Coal Region. The Triassic Coal R
the Atlantic Coast occurs in two well-defined belts in Virgi
North Carolina. The areas in each state include two northea
trending basins that vary from 20 to 40 miles in length and
14 miles in width. The basins lie in the Piedmont Plateau
Physiógraphic Province, a region of rolling topography with
low relief, and are located near the province's border with
Atlantic Coastal Plain. The Triassic rocks of the coal basi
easily eroded than either the Piedmont metamorphic and igneo
the west, or the Coastal Plains sand and gravel to the east.

The region lies in a zone that is generally warm and hum
(temperatures average 60°F) and has 45 in. of precipitation
There are, however, considerable differences between summer
summer temperatures average about 77°F and winter temperatur
43°F. Precipitation averages 4 to 6 in. per month in the su
to 4 in. per month in the winter (Reinemund 1955).

Triassic coal deposits in Virginia basins are generally
in thickness; however, one area contains seams of up to 40 f
thickness. The coal is ranked as medium to low volatile bit
is overlain by up to 650 ft. of Triassic sandstone and shale
deposits of North Carolina average 3 ft. in thickness, and t
seams range in rank from semibituminous to semianthracite.
are separated by shales up to 40 ft. in thickness and are ov
up to 250 ft. of shale, siltstone, and sandstone. Rock unit
generally tilted and faulted. The Triassic coal basins of V
North Carolina are drained by large rivers that flow southea
the ocean. Floods are common, and in North Carolina they we
responsible for closing the mines.

Springs, which are numerous along most streams in the De
(eastern North Carolina) Coal Basin, are important sources o
water supply. Subsurface water supplies here are highly var
do not yield as much as wells in either the fractured Piedmo
the northwest or the permeable sands and gravel of the Coast
the southeast.

arragansett Coal Basin. This basin extends from the Narragansett Rhode Island on the south for more than 30 miles to the east into Massachusetts, all in the Seaboard Lowland Physiographic It ranges from gently rolling hills and small lowlands to rocky line along Narragansett Bay. The climate is governed by the ting effects of Narragansett Bay and of Massachusetts Bay, which to 30 miles to the northeast. Summer temperatures generally e from 70°F to 75°F, and the average winter temperature is 30°F. pitation averages 40 to 45 in. and is evenly distributed ghout the year.

e coal is highly variable in character and quality, ranging from acite to graphite and containing much ash and a large percentage isture. There are many layers of carbonaceous shale and local of anthracite. The coal beds have been folded and compressed so they are locally in thick pockets or have been completely squeezed as a result, the coal has been broken and compressed so that large ities of quartz and other impurities have been introduced (Ashley . Anthracite beds range up to 2 ft. thick because of the zing, although its original thickness was probably only 2 to 3 The coal occupies a broad structural basin in which the rocks are derably metamorphosed and include numerous smaller folds; in other of the region, the rocks have been closely folded (Ashley 1914).

round-water resources are typical of glacial moraine country, with and generally discontinuous aquifers of sand and gravel. Valley along and below the Taunton River constitutes the other principal of ground water. Water in the underlying bedrock is controlled actures, and wells, whose productivity is sufficient for domestic may yield as much as 30 to 40 gpm (adequate for small-scale trial or municipal use).

ior Province

he Interior Province includes Michigan, Indiana, Illinois, western cky, Iowa, Kansas, Missouri, Oklahoma, central Texas, and western Arkansas, as shown on Figure 3.1 (Regions 5, 6, 7, and 8). oal reserve is 134.4 billion tons, about equal to that of the achians but more than double the known strippable coal reserves in rthern Great Plains Province. About 95 percent of the coal ves in the Midwest lies in Indiana, Illinois, western Kentucky, issouri; in 1976, those states provided 96 percent of the nce's production. Illinois contains 73 percent of the reserves ay 1978).

he discussion of the Interior Province includes a description of oal and hydrogeologic settings of the Eastern Interior Coal n, Western Interior Coal Region, Michigan Coal Basin, and Texas inous Region.

astern Interior Coal Region. The Eastern Interior Coal Region s most of the southern two-thirds of Illinois, the southwest

Central Lowlands Physiographic Province (Thornbury 1965). The topography is mainly flat or gently rolling as a result of glacial deposition and smoothing over of preglacial erosion surfaces. Relief is as low as 10 to 20 ft. per sq. mile over much of the area but can be up to 100 ft. in areas of glacial moraines. The extreme southern end of the coal province is in the Shawnee Hills section of the Interior Lowland Physiographic Province where it exhibits a wide variety of topography, from extensive glacial outwash and alluvial lowlands to rugged hills with the greatest local relief in Illinois. Bedrock exerts a strong control on topography, in contrast to the Till Plains to the north.

The Eastern Interior Region has a humid climate with an average annual precipitation of 34 in. per year and temperature of 50°F in its northern part, and 45 in. per year and 58°F in its southern portion (Geraghty and others 1973). Potential evaporation ranges from 27 in. per year in the north to 32 in. per year in the south.

Paleozoic rocks are about 15,000 ft. thick in the deep part of the basin; approximately 2,500 ft. of the accumulation is composed of Pennsylvanian rocks. Great vertical variation in lithology is characteristic of the Pennsylvanian-age rocks, resulting in more than 500 recognizable sandstone, siltstone, shale, limestone, coal, and clay units (Willman and others 1975). Many rock units are laterally persistent.

Few prolific aquifers are found in the Eastern Interior Coal Region. In Pennsylvanian-age bedrock aquifers, which are mostly thin sandstone and limestone beds, average well yields are 5 gpm or less and yields greater than 25 gpm are unlikely. Brackish or saline water occurs at shallow depths; salty water has been encountered as shallow as 100 ft. below the ground surface and generally is no deeper than 200 to 300 ft.

High-yield aquifers are found in the sand and gravel deposits associated with major glacial drainages in the Ohio, Wabash, and Illinois River Valleys and the buried Mahomet River Valley. Wells tapping those aquifers are capable of yielding more than 500 gpm, and yields of 700 to 1,000 gpm are not uncommon. Similar aquifers in the Kaskaskia and White River Valleys yield less than 500 gpm to individual wells.

<u>Western Interior Coal Region</u>. The Western Interior Coal Region covers approximately 98,000 sq. miles of the central United States. Included in the region are portions of Missouri, Iowa, Kansas, Oklahoma, Nebraska, and Arkansas. The region is situated within the Central Lowland Physiographic Province, which has generally flat to slightly rolling topography. The northern portion of the region, which contains prairie lands and hills and ridges carved from loess and till, displays local topographic relief ranging from 100 to 200 ft. In the unglaciated section, present topography is largely the result of surface rock exposures. Resistant rock types, such as sandstone, form

ridges, and outcrops of shale are located in the valleys and lands. For the most part, the land surface is gently undulating ept where zones of moderate relief (less than 200 ft.) are found r major streams. In the southern part of the region, the beds are ed and, in some areas, overturned. The southern area has rolling lands, ridge and valley sections, and eroded synclinal mountains. some southern areas, local relief may be in excess of 300 ft.

The climate in the Western Interior Coal Region is characterized by summers and cold winters. Temperatures in the southern portion rage 40°F in January and 80°F in July. In the north, temperatures rage 20°F in January and 70°F in July. Most of the area receives ween 32 and 48 in. of precipitation annually. Potential evaporation m standing bodies of water varies from 36 in. per year in the north 54 in. per year in the southwest.

The principal coal seams of the region are lower Pennsylvanian in and predominantly high-volatile bituminous in rank. They are found hin a lower series known as the Des Moines group and a less ductive upper series known as the Missouri group. The gently ing hills in the northern portion of the region were formed by the sion of glacial drift and loess. The deposits range up to 500 ft. thickness at the northern end of the basin in Iowa and extend thward into northern Missouri and small corners of southeastern raska and northeastern Kansas. In some places, coarse-grained ied channel deposits are found within the drift. Paleozoic rocks p out at the surface in the unglaciated portion of the region.

Ground-water conditions vary widely with respect to both quantity quality. The aquifers consist of three types: (1) drift, (2) uvial and buried channel, and (3) bedrock. In most of the glaciated a, the drift aquifers tend to be fine-grained and lacking in ductive zones of sand and gravel. Locally, shallow wells in the ft are adequate for rural domestic and livestock supplies, but ductive deposits are discontinuous and irregular in distribution. alluvial aquifers, which occupy the valleys of the principal eams and their tributaries, yield moderate to large supplies of good lity water. The consolidated bedrock aquifers yield limited amounts water. The shallow sandstones and limestone aquifers generally ld less than 10 gpm of medium to poor quality water. Almost all of water derived from the Pennsylvanian-age rocks is highly eralized and often impotable.

Michigan Coal Basin. The Michigan Coal Basin is located in central higan in the Central Lowland Plains Physiographic Province, an area generally low relief. Marked seasonal differences characterize the mate, although precipitation is distributed evenly throughout the ar. Winter temperatures average 15°F to 25°F, while summer peratures average 67°F to 75°F. Annual precipitation averages 30 to inches, with 24 to 26 inches of potential evapotr nspir io and

sq. miles and dip toward the center. Coal-bearing rocks crop out in only a few places along the eastern and southern edges of the basin ar are overlain by glacial drift that may be up to 850 ft. thick. The Pennsylvanian-age rocks consist of two units: a lower one that is largely sandstone and other clastic rocks, and an upper coal-bearing unit that is 200 to 500 ft. thick. The coal-bearing formation in sor areas contains gray to black shale, sandstone, and shaley limestone b in other areas it is mainly sandstone. Most of the many coal beds cover only small areas, and several are too thin for profitable mining. Only 3 of the 14 coal beds are persistent, and all of them a less than 14 ft. thick. The coal is high-volatile bituminous suitabl for domestic and industrial uses but not for coke manufacture.

Ground water occurs both in unconsolidated glacial sediments and aquifers in the underlying bedrock associated with coal beds. Ground-water quality in the unconsolidated sediments is generally potable, although it is hard and contains high concentrations of iron ground-water quality in most bedrock aquifers is poor, being brackish to saline. Freshwater aquifers in bedrock are only moderately productive. Most of the coal is below the water table, and water fro overlying sand and gravel has seeped into many of the mines so that pumping has been required during mining (Cohee and others 1950).

Texas Bituminous Coal Region. Bituminous coal in Texas occurs in three areas: (1) north-central (Fort Worth), (2) south (Eagle Pass a Santo Tomas), and (3) west (Eagle Spring, San Carlos, and Big Bend). The northern area of bituminous coal lies in the Central Lowland Physiographic Province, which has varied terrain. The surface rises gradually from east to west, with low, rolling prairies covering much of the land. The southern areas, however, are related to the Edwards Plateau, which is a southeastern extension of the High Plains; the highland surface generally rises to the west but because the coal are are near the Rio Grande River, the topography is locally dissected an rugged.

The climate, from south to north, ranges from relatively mild to fairly severe winters; generally, the summers are hot, and autumns an springs are pleasant but short. Interaction between warm moist winds from the Gulf of Mexico and cold fronts from the north and west produ sudden and dramatic changes in temperature. Average rainfall is low, ranging from 25 to 30 in. per year in the north, to less than 20 in. the south.

Because of small quantity and poor quality of coal in the west area, only the north and south areas of the Texas Bituminous Coal Region are discussed here (Evans 1974). In the north-central area, several coal seams about 5 ft. thick occur in Pennsylvania-age rocks. In the south, the Santo Tomas district contains two coal seams 2 to 3 ft. thick; these are mainly cannel* coals, and the resources are not

*Cannel coal is a non-coking bituminous coal with unique chemical anc physical properties and a higher percentage of volatile oils and gase than ordinary bituminous coal.

e. Another southern area, near Eagle Pass, supplied 30 years of
ng through a coal seam in the Cretaceous Navarro group, and still
ains large resources.

Ground water is present in surficial sands and gravels and in some
ck aquifers, although the water quality is likely to be less than
able in the north. The same is true of the water quality in the
ern areas, where generally less ground water is available near
surface. One of the major constraints against development of the
el coal resources in the Santo Tomas District is the "potential
of a readily available water supply that would support major
strial development and mine-mouth operations" (Evans 1974).

Coast Province

The Gulf Coast Province includes parts of Alabama, Arkansas,
siana, Mississippi, Tennessee, and Texas (Regions 9 and 10 in
re 3.1). Information on the extent of shallow and deep coal
rves is presently being refined. The most recent regional
mates place Gulf Coast shallow lignite reserves at 22.5 billion
(Luppens 1978). Gulf Coast lignite deposits do not have a long
expectancy relative to the other major coal regions in the United
es (Murray 1978). Large-scale underground mining of lignite is
ently not economically feasible because of geological conditions,
n-situ gasification may have a good potential for tapping deeper
ite beds.

The Gulf Coast Lignite Region extends more than 1,000 miles from
Texas-Mexico border to approximately the Alabama-Georgia state
. The topography of the Gulf Coastal Plain is variable and
ists of several subregions that include the Belted Coastal Plain,
coastwise terraces of southern Texas, Alabama, and Florida, and the
issippi and Red River alluvial valleys.

Generally, precipitation decreases from east to west in the western
half of the region and increases from north to south in the eastern
ion. The greatest precipitation occurs in southern Alabama (more
60 in. per year) and the least in southwest Texas (16 in. per
). The potential evapotranspiration ranges from 40 in. to more
54 in. per year. Winters are moderate to cool and summers are
Record summer temperatures throughout the region exceed 100°F.

The Tertiary rocks of the Gulf Coast consist almost entirely of
inal marine and coastal plain sediments. They are characterized by
ically alternating fine-grained and coarse-grained sequences. The
lignite-bearing units are the Midway, Wilcox, Claiborne, and
son groups. Most commercially exploitable lignite deposits occur
ine-grained (clays and silts) portions of the Wilcox. The
mentary rocks of the Gulf Coast are generally poorly consolidated
dip gulfward at about 1 degree.

Ground water in the Gulf Coast Lignite Region is relatively
d t a d of good q al ty Yie s o m 1,0 0 gpm hav ee

of fine-grained sands, silts, and clay, while gravel units and limestone beds are found in Mississippi and Alabama, respectively. The Carrizo-Wilcox aquifer can yield up to 3,000 gpm in Texas; the Wilcox aquifers in Mississippi and Alabama yield up to 2,000 gpm, usually for domestic or agricultural purposes. Water quality varies through the Wilcox. Freshwater predominates, although in south Texas, the Wilcox aquifer contains slightly saline water.

Western United States

Coal resources of the western United States are found in the Northern Great Plains, Rocky Mountain, and Pacific Coast Coal Provinces (see Figure 3.1). Production in Wyoming, Montana, and North Dakota accounts for 64 percent of the total for the western U.S. (Table 3.1), almost all of which is derived from the Northern Great Plains Province. Of the remaining 36 percent of western coal production, 33 percent is from the Rocky Mountain Province and the remaining 3 percent from Washington in the Pacific Coast Province.

In Table 3.3, the size of the total coal-bearing areas is compared with the total area of each state; it shows that the coal-bearing areas of those states cover 28-45 percent of their total areas (National Research Council 1974). The physical characteristics of each of the three provinces, including the general hydrogeologic conditions, are described below.

Northern Great Plains Province

The Northern Great Plains Province is generally characterized by low relief and lies totally within the Great Plains Physiographic Province. Annual precipitation varies between 10 inches and 26 inches, with much of the region receiving 12 inches to 16 inches of precipitation a year (Northern Great Plains Resources Program 1974). Potential evaporation (open water) ranges up to about 45 in. per year (Geraghty and others 1973). Temperatures rarely exceed 38°C in the summer and -40°C in the winter.

The majority of the province is underlain by thick sequences of Cretaceous and Tertiary sediments. Coal deposits are found principally in the Tertiary Fort Union and Wasatch formations. Figure 3.1 shows the approximate surface extent of the deposits. Coals are low-sulfur subbituminous in the Powder River basin region of Wyoming and southeastern Montana, medium- to high-volatile bituminous in the north-central region of Montana, and lignite in the Fort Union region of eastern Montana and in the Dakotas. In the Powder River region, numerous coal seams ranging from 5 to 30 m in thickness are within 60 m of the surface. Coal is associated with interfingerings of channel

LE 3.3 Size of State in Relation to Size of Coal-
ring Areas for Western Region

e	Total Area of State (Sq Miles)	Area Underlain by Coal-Bearing Rocks (Sq Miles)	Percent
ona	113,090	3,040	3
orado	104,247	29,600	28
ana	147,138	51,300	35
Mexico	121,666	14,650	12
th Dakota	70,665	32,000	45
th Dakota	77,017	7,700	10
n	84,916	15,000	18
ing	97,914	40,055	41
TOTAL	816,653	193,345	24

In the Northern Great Plains Province, the occurrence, movement, quantity, and quality of ground-water resources vary widely in accordance with the character of the underlying rocks or unconsolidated material. Shallow ground water is the principal source of domestic, agricultural, and livestock supply throughout the region. Ground water occurs in the alluvium associated with perennial streams and in associated sandstone, coal, and clinker deposits. Yields of wells in the alluvial deposits associated with the Missouri River, Yellowstone River, and their major tributaries are generally adequate for crop irrigation. Wells in deposits associated with smaller tributaries generally range from 10 to 50 gpm and are relied upon for domestic, stock, and local irrigation use. Yields of wells in sandstone associated with coal regions range from 10 to 50 gpm. Wells finished in saturated coal seams usually have yields of less than 10 gpm. Saturated clinker deposits yield tens to hundreds of gallons per minute depending on the degree of fracturing. However, developing wells in such burn areas can be extremely difficult.

Ground-water movement in the region is influenced by topography, permeable unconsolidated and consolidated sediments, and the major surface-water systems. Generally, precipitation as rain and spring snow melt recharges the permeable sandstone and clinkers in the topographically higher regions associated with surface-water drainage divides. A portion of the recharge moves downward to recharge underlying formations. Where less permeable strata are encountered, a portion also moves down gradient and discharges as spring flow and to perennial streams and associated zones of phreatophytes.

Deposits of sandstone, clinker, and coal act as the principal consolidated aquifers in the coal-bearing Fort Union and Wasatch formations. Alluvium and adjoining deposits of sandstone are directly recharged by precipitation if precipitation occurs in sufficient quantities. These units discharge to perennial streams. Clinker deposits tend to be highly fractured and, where water is available for recharge, large volumes are transmitted. Deeper intermediate and regional flow systems occur beneath the coal-bearing units. The principal aquifer systems are the upper Cretaceous sandstones of the Hell Creek and Fox Hills formations and the regional Madison group limestone aquifer system of Mississipian age. They are recharged directly from precipitation or stream flow at outcrops and indirectly by leakage through confining beds. Discharge occurs along down-gradient outcrops and through confining beds to aquifers having lower hydrostatic pressures.

Well yields vary widely. Yields from the Cretaceous sandstone are generally less than 100 gpm. The Madison group has been used for industrial water supply in Montana and has been researched for potential use in a coal slurry pipeline in Wyoming. Proposed industrial wells could yield up to 2,000 gpm.

Ground-water quality also varies widely. Alluvial deposits usually contain a calcium-magnesium, sodium-bicarbonate sulfate water that has total dissolved solids of less than 2,000 mg/l. In or near recharge

areas, sandstone, coal beds, and clinker usually contain a calcium-magnesium sulfate water. The total dissolved solids content is usually less than 1,000 mg/l. Aquifers down gradient from the recharge areas generally contain more sodium; in many areas, the increased sodium is accompanied by decreased calcium, magnesium, sulfate, and total dissolved solids because of cation-exchange and sulfate-reduction processes. Clinker that receives recharge from coal beds generally contains water that is similar in quality to that of the coal beds. The Cretaceous aquifers below the coal-bearing units usually contain water that is a sodium-bicarbonate type having a total dissolved-solids content of less than 1,500 mg/l. The Madison aquifer water is a calcium-bicarbonate type that has a total dissolved solids content of less than 1,000 mg/l near the recharge areas and a high total dissolved-solids content of calcium sulfate down gradient.

Rocky Mountain Province

The Rocky Mountain Province contains the rugged northwest-southwest trending mountain ranges of the Rocky Mountain System Physiographic Province and the dissected plateau and valley region of the Intermontane Plateaus Physiographic Province. Annual precipitation varies from less than 10 in. in the southwestern Colorado Plateau Region to more than 50 in. in the mountains. Potential evaporation (open-water) varies from about 30 to 80 in. per year (Geraghty and others 1973); the areas of highest potential evaporation correspond generally with the areas of lowest precipitation. Temperatures in the northern portion of the area are similar to those of the Northern Great Plains Province. In the southern portion of the area, summer temperatures exceed 38°C and go below freezing for varying periods in the winter months.

The mountainous and plateau regions are composed of Cretaceous and Tertiary sedimentary deposits that contain subbituminous and bituminous coal. Coal deposits in the Rocky Mountains occur in intermontane basins and are relatively restricted in area. The Bighorn basin region, Wind River region, Green River region, Denver basin, and San Juan Basin contain thick sequences of sedimentary rocks in which deposits of subbituminous coal occur. The Colorado Plateau is composed of many local structural basins that contain bituminous and subbituminous coal.

All states utilize surface-mining techniques; Arizona, New Mexico, and Wyoming have major operations. An important portion of the region's coal production also comes from underground mining.

The occurrence, movement, quantity, and quality of ground-water resources in the Rocky Mountain Province vary widely with the diverse climatic, geologic, and topographic settings of the province. Within the coal-bearing regions of the province, unconfined ground water is found associated with alluvial deposits occurring in valleys and ephemeral drainages. Throughout the province, alluvial aquifers are the principal sources of domestic, agricultural, and stock supply.

high as 1,000 gpm. However, most wells yield less than 100 gpm and, the arid parts of the province, less than 25 gpm. Ground water foun in consolidated rocks in coal regions is usually under confinement. Sandstone is generally the highest yielding material, providing up t 100 gpm. Fractured shale and coal also yield water to wells in some regions; however, yields are usually less than 10 gpm.

Ground-water movement in the province is influenced by topograph the occurrence of permeable unconsolidated and consolidated sediment and major surface-water drainages. Generally, precipitation recharg consolidated formations at outcrops in topographically high areas ar alluvial deposits associated with perennial and ephemeral drainages. Stream flow in the forms of flash floods and spring snow melt also recharges associated alluvial material and permeable consolidated units. A portion of the recharge moves downward to recharge underly formations, discharges as spring flow when less permeable strata are encountered, and discharges to perennial streams and associated zone of phreatophytes. Zones of perched ground water and contact springs are usually encountered beneath topographically high regions and are especially common in areas of the arid southwest. Deeper confined ground-water systems usually associated with extensive sandstone deposits are also present beneath much of the southern portion of th province.

Ground-water quality varies widely. Aquifers associated with recharge areas usually have a total dissolved-solids content of less than 500 mg/l. In down-gradient portions of the aquifers associated with the coal resources, total dissolved solids concentrations are m than 1,000 mg/l; concentrations greater than 3,000 mg/l are not uncommon in the more arid regions (USGS 1979). The water quality is function of solution, ion exchange, and sulfate reduction. Calcium, magnesium, sodium, sulfate, and biocarbonate are the principal ions present in the water.

Pacific Coast Province

The Pacific Coast Province includes the Pacific Border and Cascade-Sierra Mountains Physiographic Provinces and portions of the Columbia Plateau and Basin, and Range Physiographic Provinces. Annu precipitation varies between 13 cm and 360 cm, with the majority of region receiving in excess of 75 cm annually. Potential evapo-transpiration varies up to 120 cm annually in the arid California basins (Geraghty and others 1973). Temperatures in the province exc 38°C in the arid areas during the summer and are well below freezing the mountains during the winter.

The province consists mainly of Tertiary sedimentary and volcan rocks that are often complexly folded and faulted. Coal deposits ar found in the valley areas. However, because the bedrock is intense deformed, most coal deposits in the province are relatively small an discontinuous. A few small deposits of lignite and subbituminous c are in California and Oregon. The largest coal fields in the regio are the Tertiary subbituminous and low volatile

bituminous coals of Washington State. Coals are associated with interbedded siltstone, sandstone, and conglomerate. Coal beds in the Washington State Centralia - Chehalis district range in thickness from a few inches to 40 ft. and have an average thickness of 6 to 8 ft.

Domestic water supply is obtained from the near-surface ground-water system when surface water is not available. The Skookumchuk formation is composed of sandstone, siltstone, clays, and coal and is saturated. The formation is recharged in the higher elevations to the west and becomes confined to the east. Wells finished in more permeable zones of the formation will yield water to wells in sufficient quantities for domestic supply.

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CHAPTER 4

THE GENERIC EFFECTS OF COAL MINING ON GROUND WATER

INTRODUCTION

Mining of coal or any other mineral is a disruptive process that can temporarily or permanently alter ground-water systems. A mining operation that changes any portion of the geology or chemical framework of a ground-water or surface-water system will affect the existing and post-mining characteristics of the system. Generally, coal mining has two kinds of effects on ground water:

1. An initial decrease in the quantity of ground water owing to removal of aquifers or dewatering to enable the mining activity to proceed.

2. An alteration in the quality of ground water owing to chemical changes of mine-related materials or to coal gasification products.

The significance of the effects on the quality and quantity of ground water depends on:

- The value of the ground-water resource;

- The hydrologic conditions in the mined areas; and

- The amount of surface or near-surface material that is disrupted.

These points should be kept in mind when reviewing the general effects of coal mining on ground water, as presented in this chapter.

PHYSICAL EFFECTS

During active operations, mines act as ground-water sinks in the flow systems they disturb (Figures 4.1a and b). Mines intercept ground

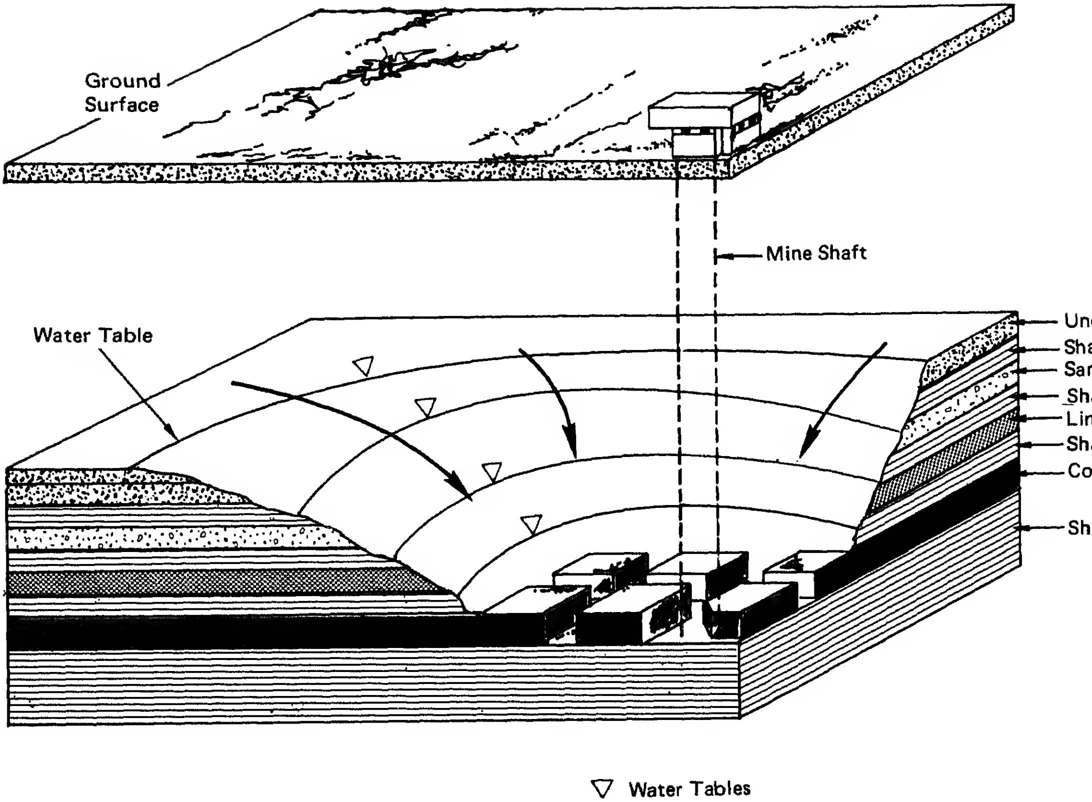


FIGURE 4.1a Hypothetical Ground-Water Cone of Depression Developed by Underground Min

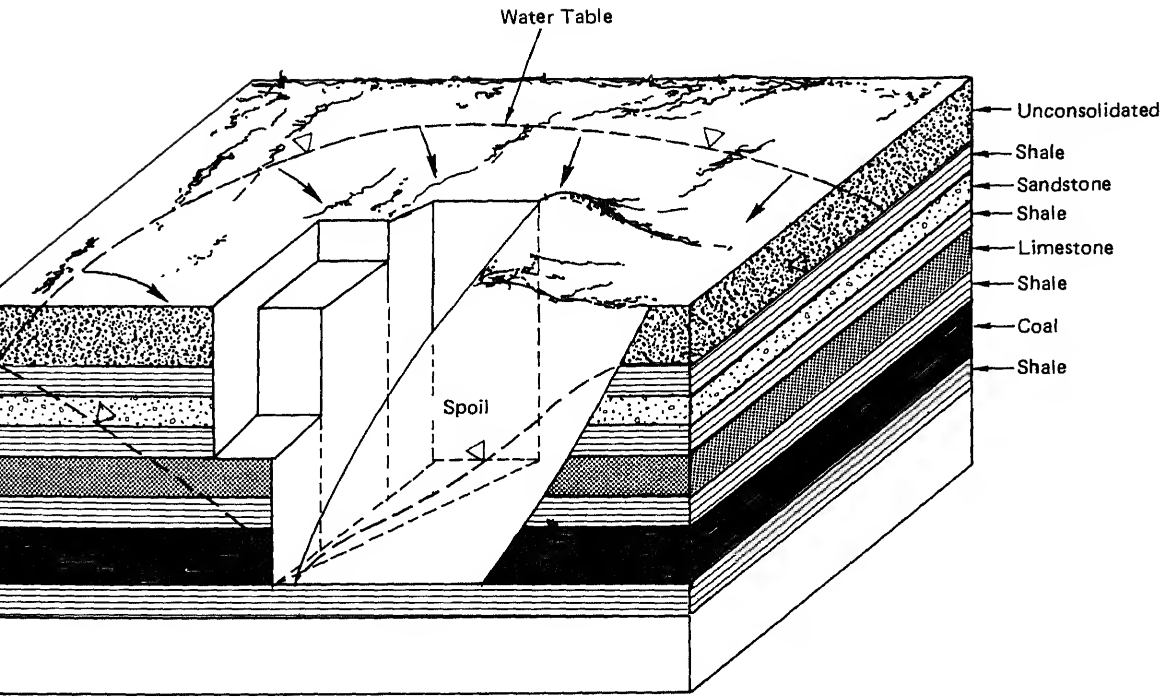


FIGURE 4.1b Hypothetical Ground-Water Cone of Depression Developed by Surface Mining

responses: (1) the presence of ground-water inflow to shafts and pits, and (2) a lowering of water levels or hydrostatic pressures in some areas surrounding the mines.

Effects During Active Mining Operations

A mine, whether surface or underground, acts much like a large-diameter well because any water encountered is removed by pumping or gravity flow. Potentiometric surfaces will be affected, and a "cone of depression" usually will develop around the mine. The exact dimensions of the depressed zone will be a function of several factors, including the position of the mine within the ground-water flow system, hydraulic conductivity, and storage capacity of the penetrated aquifer(s).

Many mines operate along coal-bed outcrops or subcrops. Such mines disturb the "edges" of ground-water flow systems: areas of natural ground-water recharge or discharge. Natural hydrostatic pressures are not great in these areas, and the resultant inflow rates to mines are correspondingly small. The excavations gradually reduce the lateral extent of the aquifers, and hydrostatic pressures adjust slowly to the new conditions. Most influent water to surface mines in these places consists of intercepted ground water, because mine excavations are expanded too slowly to induce significant flow from storage. Hydrostatic-pressure declines, or well-water-level declines, associated with such gradual releases of ground water from storage are also very gradual and commonly are not perceptible more than a hundred meters from the pits. Influent rates to surface mines along aquifer outcrops or subcrops are so low that most cuts are dried by evaporation, and water levels in nearby wells are only slightly affected by the extremely slow rates of storage depletion. Exceptions occur where disturbed aquifers such as alluvium and clinker have abnormally high hydraulic conductivities. Because of their high conductivities, saturated alluvium or clinker can provide enough mine inflow that dewatering of pits or of areas adjacent to pits can become serious operational problems. However, the large volumes of influent do not generate correspondingly extreme water-level or hydrostatic-pressure declines because storage capacities of these materials are usually several powers of ten greater than those of the bedrock aquifers and because the affected area is relatively small.

Mines that penetrate the interior parts of ground-water flow systems cause effects considerably different from those of mines along aquifer outcrops. Pre-mining hydrostatic pressures in such aquifers are much greater and storage coefficients are generally very low; therefore, declines of water levels in wells can occur over distances of several kilometers from the pits. Rates of mine influent that must be pumped to surface watercourses are also greater than those at mines along outcrops but generally are not great enough to cause operational problems. Exceptionally higher inflow rates sometimes occur when pits encounter areas of lineaments of abnormally high hydraulic

conductivity, such as occur along faults or tight folds that have fractured the aquifers.

Declines in water levels in aquifers that lie stratigraphically below those being mined can also occur, even though the aquifers are not physically disturbed (Figure 4.2). Strata that separate aquifers are generally beds of clay and shale that have very low hydraulic conductivities. Nevertheless, the dewatering of pits and adjacent areas can create strong vertical hydrostatic-pressure gradients that induce substantial vertical inflow where large areas are involved. Augmenting the vertical leakage through confining beds are those flows created by leakage through unplugged drill holes (common in mining areas) and those caused by aquifer expansion (unloading) resulting from removal of the large tonnages of coal and overburden. Regardless of the causes of declines in water level in deeper, undisturbed aquifers, the changes are substantially less than those occurring in the aquifers being mined.

Post-Mining Conditions

When mine pits are backfilled or when shafts are plugged, ground water readily re-enters the mine spoil. With the cessation of dewatering, hydrostatic pressures in nearby aquifers and water levels in nearby wells begin to recover toward pre-mining conditions (Figure 4.3). In surface mines, differences between pre- and post-mining conditions of ground-water flow are governed by relations of hydrologic characteristics of mine spoils to those of pre-existing undisturbed aquifers.

Bedrock aquifers have wide ranges of hydraulic conductivities and generally very low storage coefficients. Similar conditions have been found in rubble zones at the bases of mine spoils probably because of wasted coal and other rubble left along the mine floors. The mine-floor aquifers may be confined between underlying clay and silt beds and overlying mixtures of clay, silt, and sand. They contain ground water under artesian (greater-than-atmospheric) pressures and, thus, have very low storage coefficients, much the same as those of the coal seams and sandstones. It is unlikely that hydraulic conductivities of spoils in any mine will be the same as those of the pre-existing bedrock aquifers. The spoils do transmit enough water, so that they are not barriers to ground-water flow. They seem to be somewhat more conductive than the undisturbed bedrock aquifers and allow correspondingly greater rates of water flow.

The occurrence and flow of ground water in the spoils does not imply the presence of ground water that is easily available to wells. Spoils are unconsolidated mixtures of clay, silt, sand, and rock fragments that, when saturated, make the construction of wells difficult. Substantial quantities of water may be present, but pumping of fine-grained materials in wells in mined lands is a problem.

The ground water that first enters mine spoils enters laterally from adjacent undisturbed aquifers. Later, recharge to the spoils can

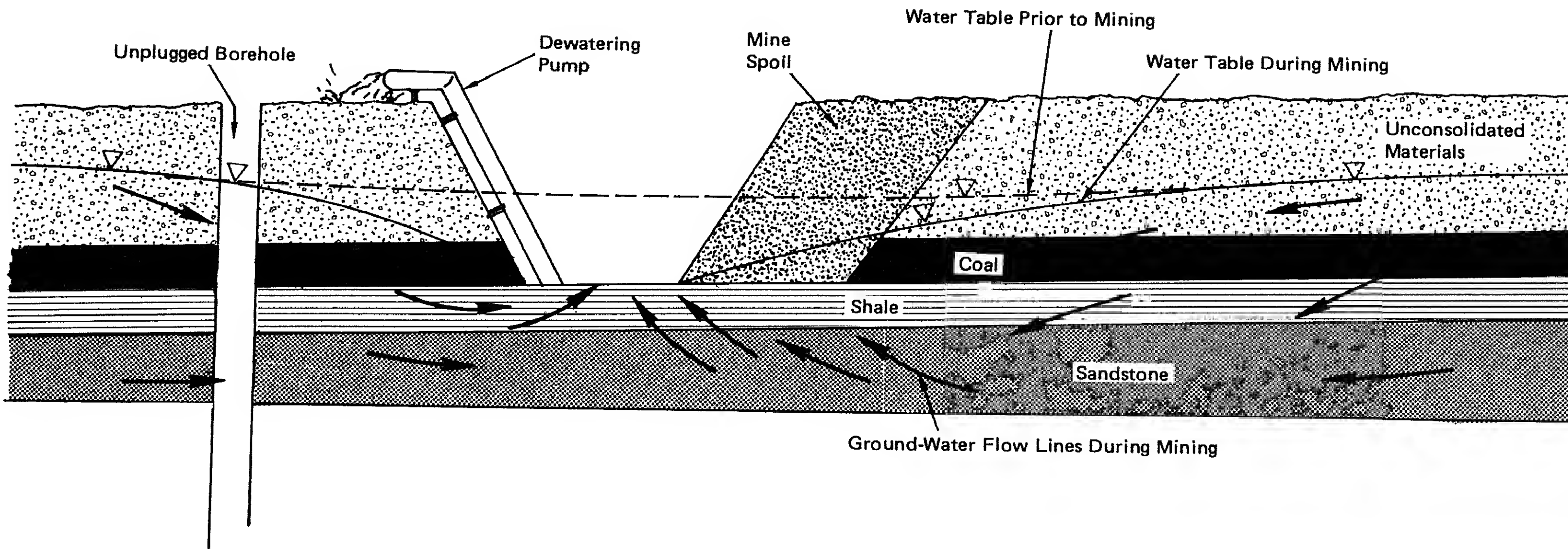


FIGURE 4.2 Vertical Leakage to Surface Mines (through lower conductivity beds separating aquifers from the surface and through unplugged bore h

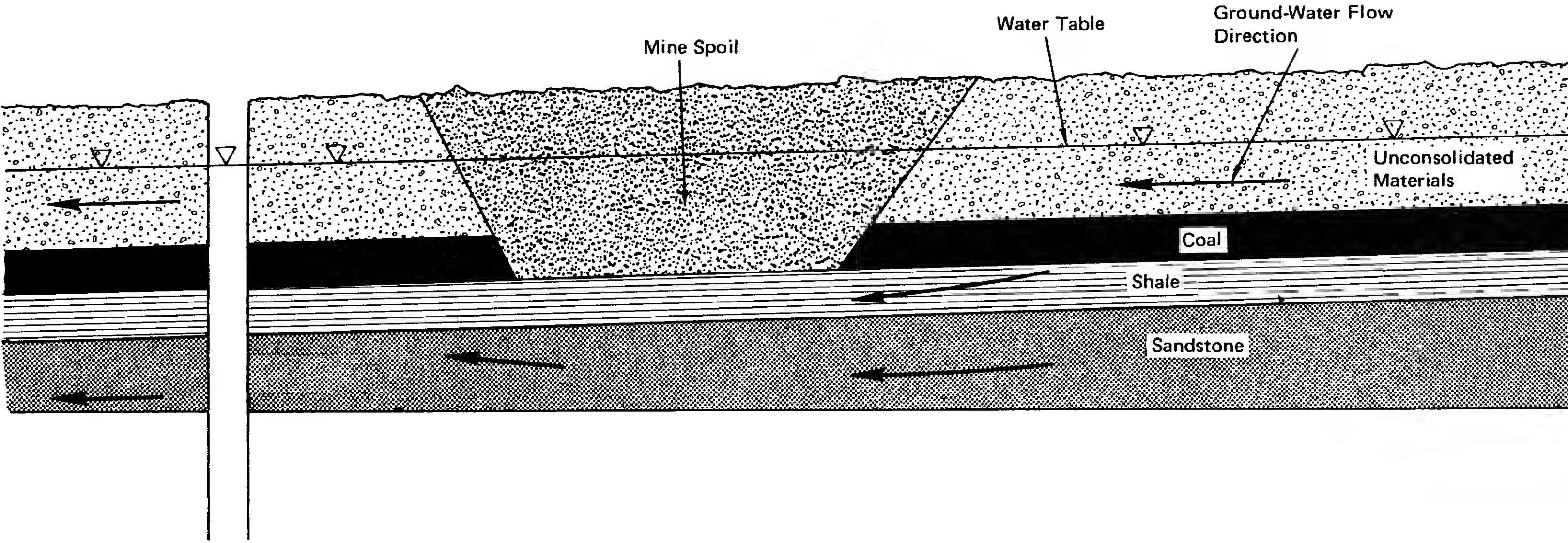


FIGURE 4.3 Re-establishment of Previous Ground-Water System after Surface Mining

the spoils begins after infiltration has wet the previously dry materials to the degree that gravity drainage to the saturated zone can occur. Depending on many factors, the wetting process can be rapid or last for decades. Recharge is much more rapid in the East and Midwest than in the West because of more precipitation and less evapotranspiration. In some western mines, sodic clays are abundant enough in the spoils that their swelling prohibits any infiltration, and subsequent recharge through spoils depends on reclamation procedures. For these mines, where the surface is reclaimed to "approximately the original contour" and revegetation with vigorous plants is successful, recharge is minimal; most precipitation leaves the area as direct runoff or is lost through evaporation and transpiration. Where closed drainages, such as those around ponds or impoundments, are left after reclamation, recharge to the ground-water system is maximized.

Where recharge to spoils is significant, changes in ground-water storage and stream flow can alter the water balance. The increased recharge to spoils causes more uniform temporal distribution of stream flow on an annual basis. The spoils provide temporary storage of water during periods of high precipitation and snow melt and release it to the streams during drier periods. The results are a decrease in periods of high flows or floods and an increase in the base flow of streams during periods of low precipitation. The temporary storage of ground water in mined lands is beneficial with respect to water availability but, in many cases, can be detrimental because of water-quality degradation.

CHEMICAL EFFECTS

Mining activities can cause changes in the chemical composition of ground water. In some cases, the changes may impair the quality of the ground water for existing or future uses. In other cases, the changes will have no significant influence on the usability of the water, or the changes will be so slight as to be difficult to detect. In situations where degradation in the quality of ground water is occurring as a result of non-mining activities, the influence of mining might be secondary and less significant than the other influences.

Chemical Constituents

Chemicals that occur in degraded water generally are the same constituents that occur in uncontaminated water. The geochemical processes that cause degradation of ground water because of mining typically are the same processes that operate in systems unaffected by mining. However, mining has the potential to drastically alter the relative influence of various geochemical processes and, consequently, to cause ground water to have undesirable concentrations of various chemicals.

All ground water contains dissolved solids, consisting primarily of a group of constituents referred to as major ions.

sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), bicarbonate (HCO_3^-), and sulfate (SO_4^{2-}). Ground water that contains less than 1,000 mg/l of dissolved solids is referred to as fresh. If the dissolved solids range from 1,000 to 3,000 mg/l, the water is slightly brackish; if the range is 3,000 to 10,000 mg/l, the water is brackish. Saline water has dissolved solids in the range of 10,000 to 50,000 mg/l, and brine water has dissolved solids above 50,000 mg/l. (Seawater has approximately 35,000 mg/l of dissolved solids.) Uncontaminated fresh ground water is normally suitable for human consumption, for livestock, and for most industrial uses. Slightly brackish water may not be suitable for those uses, depending on the relative amounts of the various major ions and trace elements. Brackish, saline, and brine waters are never suitable for human consumption. In some cases, brackish water can be used for livestock, although saline and brine waters never can.

In addition to the major ions, all ground water contains a large number of minor and trace constituents. The minor constituents occur in concentrations that are normally less than the major-ion concentrations and greater than the trace constituents. A common minor constituent, for example, is silica (SiO_2), which normally occurs in the range of 2 to 20 mg/l. Silica is of no consequence with regard to suitability for consumption by humans or livestock. The amount of dissolved iron (Fe), another minor constituent, depends on the oxidation status of the iron and can occur at levels of a milligram per liter to tens of milligrams per liter. In water with pH levels above 8, carbonate (CO_3^{2-}) may also exist in this concentration range. In ground water unaffected by man's activities, nitrate (NO_3^-) rarely occurs at levels above a fraction of a milligram per liter; because of the influence of agriculture and disposal of sewage on land, however, shallow ground water in some regions in which coal mining occurs contains NO_3^- at levels ranging from one milligram per liter or tens of milligrams per liter. Water with more than 45 mg/l of NO_3^- is unfit for human consumption.

The trace elements most relevant to mining and water quality are those for which maximum permissible limits generally are specified in drinking water standards. Included are arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver. Although natural ground water usually contains trace elements at levels below the limits considered safe for drinking water, there are some exceptions. In assessing the effect of mining activities on ground water, the chemical composition of the existing ground-water systems should be well documented prior to mining.

All of the chemical constituents mentioned thus far are inorganic elements or compounds. Ground water naturally contains organic compounds, the total amount of which is normally expressed as dissolved organic carbon (DOC). Uncontaminated ground water generally contains between 1 and 20 mg/l of DOC, although in some areas where coal occurs, values in the range of 20 to 50 mg/l of DOC are observed. Natural DOC can cause water to have a slightly yellow or brownish color, but no limit on DOC is specified in drinking water standards.

However, an organic constituent that can occur naturally in ground water and for which maximum permissible limits generally are specified for drinking water is phenol. Phenol refers to a class of compounds in which one or more hydrogen atoms in an aromatic nucleus have been replaced by a hydroxyl group (OH). It is a constituent of the tars of both coal and wood. Natural phenol can occur in ground water at concentration levels considered unsafe for drinking water, but few data exist on phenol concentrations in existing or potential coal-mining areas.

Mining generally affects ground-water quality by changing the concentrations of dissolved compounds in the water rather than by adding new constituents to it. The changes are caused by a release of the compounds from geological materials disrupted by mining. The release results from (1) an increase in the surface areas of geological materials exposed to chemically aggressive subsurface water; (2) an increase in the chemical aggressiveness of circulating subsurface water, often because of the presence of oxygen; and (3) an increase in the rate of recharge or circulation of subsurface water. The changes to the hydrogeochemical system occur temporally in four phases:

<u>Phase 1</u>: Pre-mining phase; represents a system that has evolved over many thousands of years during which a relatively unchanging set of hydrological and geochemical constraints existed.

<u>Phase 2</u>: Mining phase; represents a period of continued disruption and disequilibrium.

<u>Phase 3</u>: Reclamation or abandonment phase; represents a period in which the hydrological and hydrogeochemical system starts to adjust to the conditions of reclamation or abandonment.

<u>Phase 4</u>: Post-mining phase; represents a period in which the system has, to a major extent, adjusted to the post-mining conditions so that the rate of change in the ground-water system is small, relative to phases 2 and 3.

Geochemical Processes

Overburden materials can yield dissolved solids to water flowing through them, primarily as a result of dissolution of minerals or of oxidation of materials. Mineral dissolution can occur in the absence of oxidation, or in combination with oxidation processes which greatly enhance the extent to which mineral dissolution occurs. The greatest potential for degradation of water quality occurs where the overburden contains appreciable concentrations of FeS_2 (referred to here as pyrite, although in

solution. If the geological materials are incapable of buffering the solution, the pH of the water (pH negative logarithm of the hydrogen ion concentration) declines, in some cases to values as low as 2 or 3. Such affected water is an acidic solution with a high content of sulfate and iron and, as such, is unsuitable for all domestic and agricultural uses. Fortunately, in many areas of coal mining and particularly in the western United States, the overburden materials have considerable capacity to neutralize the acid generated by pyrite oxidation. The neutralization capacity is primarily a result of calcite ($CaCO_3$) and dolomite [$CaMg(CO_3)_2$] in the overburden. The minerals are moderately soluble in the presence of acidic water. Hydrogen ions combine with the carbonate to form bicarbonate (HCO_3^-), thereby raising the alkalinity of the water. The bicarbonate, calcium, and magnesium ions resulting from dissolution of calcite and dolomite raise the total dissolved solids of the water. In acidic water, iron remains in solution at high concentrations, but in the alkaline water, iron concentrations are normally low due to the solubility constraint exerted by iron carbonate. Waters that are strongly influenced by pyrite oxidation but that are neutralized as a result of the presence of calcite or dolomite commonly have concentrations of dissolved solids that render them undesirable for domestic or agricultural uses. The neutralized waters, however, are much less damaging to the ecology of surface water systems.

The primary process causing severe degradation of water in areas of coal mining is pyrite oxidation, which occurs because of the presence of oxygen and water in the disrupted overburden. Below the water table, the oxidation process is not very active because the availability of oxygen in the geological materials there is severely restricted by the very low solubility limit for oxygen in water. Above the water table, oxidation of pyrite can be very active provided that the pore spaces in the geological material receive oxygen if air comes in from the atmosphere or is trapped in the pore spaces as a result of mining and redeposition of the overburden. Infiltration of rainfall or snow melt causes the oxidation products and associated weathering products in solution to move downward to the water table and become part of the dissolved solids in the ground-water systems.

Pyrite, when oxidized, is a strong acid producer. Even very small amounts of it in the geological material can, when the hydrological and geochemical conditions are suitable for oxidation, produce a great deal of sulfate and acid. For example, when expressed as a weight percentage of the bulk geological material, less than 1 percent pyrite, in some circumstances, may be sufficient to cause severe degradation of ground-water quality.

Pyrite oxidation in mined areas in which the buffering capacity is low causes an increase in dissolved solids and a decrease in the pH of the ground water. In addition, in response to the pH conditions, pyrite oxidation may cause exceptionally high concentrations of toxic metals in the ground water. For example, metals such as lead, copper, nickel, zinc, and cadmium tend to exist at much higher concentrations in acid waters than in neutral or alkaline waters. Higher

because of desorption of metals from particle surfaces in the geological materials.

Although reduced sulfur occurs in pyrite in some Western areas, soluble sulfate salts are normally the cause of high sulfate concentrations in ground water in mines and mined land; in some areas there is a possibility that oxidation of reduced sulfur in organic form (i.e., in coal or coal fragments in overburden) produces sulfate and associated weathering products. In a mining area, the coal seam itself is typically the major acid producer because of pyrite within the coal. Sources of alkalinity are generally found in the overlying rocks or unconsolidated overburden. Consequently, mines that disrupt the overlying material, such as strip mines, can cause alkalinity to be produced in the strata that contain calcite and dolomite. In contrast, mines that penetrate only the coal seam, such as underground and auger mines, disrupt the potential acid producer without affecting the alkalinity production potential of the overlying strata.

In some geological settings, the water quality may be degraded by inflows or intrusion of natural ground water that is brackish or saline. Where brackish or saline ground water discharges into a mine, the flow of the mine drainage to surface water causes deterioration in surface-water quality. Or, where mining is facilitated by pumping to limit ground-water inflow to the excavations, natural ground water of poor quality may be discharged to surface waterways.

The quality of drainage water from a mine depends on many factors, such as climate, ground-water flow patterns, permeability distribution, overburden mineralogy, and chemical constituents in the coal strata. Thus prediction of the quality of drainage water from a particular mine site is difficult.

Chemical Effects in the East

In the eastern United States, there is a large excess of precipitation relative to evapotranspiration, whereas in the West, there generally is a relative deficiency of precipitation. Ground-water systems in the East, where recharge is much more frequent, are generally more active than systems in the West. Because of the major differences in the two regions, scales of change are best considered in a regional context.

During the extraction of coal, associated rocks are disrupted and exposed to the atmosphere. The mining technique used at a particular site determines the degree to which the coal horizon or the overburden is disturbed and greatly affects the quality of water from drainage. Because of mining economics, seams deeper than 350 ft. are usually mined underground from shafts. Thick, nearly horizontal, near-surface outcroppings of coal are commonly mined from entry shafts that are open to the ground surface. If the overburden is sufficiently thin, the coal is surface mined.

How does the type of mining operation affect the chemistry of the mine drainage? In most underground mining processes, only the coal seam and the strata immed e y adjacent to the seam are disarranged

those horizons affects the quality of the drainage from the active mine. Upon completion of the mining phase, shafts and tunnels located below the water table become flooded and the exposed strata weather in a static system. Entry shafts located in hillsides may flood if they dip down and away from the mine opening, or they may become perpetual gravity drains if they dip toward the mine opening. In the first situation, the geochemical environment becomes a static system after flooding progresses throughout the shaft; in the second, unless the entry is sealed, a dynamic condition is maintained. Obviously, oxidation rates will vary between the different environments.

On occasion, roof material may collapse and cause fractures and joints to propagate upward, thereby increasing the thickness of the overlying strata that becomes exposed to weathering processes. In that situation, the quality of the mine drainage may be modified by the additional chemicals originating from the newly exposed strata. The varying levels of upward migration of fractures induced by roof collapse, coupled with the physical and chemical variations of overburden characteristics, make a response in the quality of the mine drainage difficult to plan.

In surface-mining operations, however, a variety of rock types making up the overburden are disrupted and exposed to the atmosphere. Contingent upon the hydrogeology of the area and the depth of the mine cut, the water table may be intersected and ground-water flow induced into the surface mine. During operation of the mine, the water is pumped out. When the mine is backfilled, fragmented overburden becomes the fill material and medium for infiltrating waters. With time and increasing infiltration events, a water table becomes established in the backfill of the reclaimed mine. The rock materials inundated by water are placed in a static oxygen-deficient geochemical environment, whereas materials in the vadose zone (above the water table but below the land surface) are in a humid, oxidizing environment that is frequently flushed by infiltrating waters.

Thus, the location of the mine with respect to the hydrogeologic regime determines the spatial and temporal dimensions of the environmental impact. Other mining techniques, such as mountaintop removal and head-of-hollow fill, can be applied to one of the representative geologic settings illustrated in the following section to ascertain the environmental impact.

Regardless of the specific setting or the mining technique, mining rearranges the natural sequence of coals and associated rock strata and places them in contact with atmospheric conditions. In that new environment, a host of interrelated factors, including oxygen, humidity, and iron bacteria, combine to accelerate the rock-weathering processes which in turn cause radical changes in the chemistry of water contacting the weathering strata.

In some cases, mineralogy is such that the rock remains inert and neither acidity or alkalinity is produced, making the environmental impact from mining minimal. For example, a pure sandstone made up primarily of quartz will not undergo rapid chemical or physical decomposition in most coal mining operations. Drainages in contact with the rocks will be neutral and have low specific conductivities.

However, in rocks with different mineralogic components, acidity o alkalinity may be produced. In the Appalachian coal regions, the dissolution of calcareous strata (limestone and associated dolomit generates alkalinity, whereas the oxidation and dissolution of iro disulfides (primarily pyrite) produces acidity.

From an environmental viewpoint, alkaline drainages originatin from calcium-magnesium carbonate systems do not harm the hydrologi regimes. The natural limits of carbonate solubility at a given pa pressure of carbon dioxide give rise to environmentally acceptable levels of pH, alkalinity (primarily bicarbonate), and hardness (as calcium and magnesium) in highly buffered hydrologic systems. Und atmospheric conditions, where the partial pressure of carbon dioxi level is $10^{-3.5}$ atmospheres, the alkalinity (as $CaCO_3$) produced by calcium carbonate is approximately 50 mg/l. If the carbon dioxide level is increased to 10^{-1} atm., as might be expected in a heavily vegetated and organic-rich soil horizon, the concentration of alkalinity is increased approximately eight times. Once equilibri achieved with respect to calcium carbonate-bicarbonate systems, th concentration of alkalinity is fixed by the solubility of calcium carbonate and the partial pressure of carbon dioxide. Thus, the hydrologic system is saturated with calcium carbonate, and further contact with calcareous material does not effectively increase the concentration of alkalinity beyond the concentrations established equilibrium conditions.

Some recently developed analytical techniques, used to charact the acid-base account of rock overburden materials, neglect to tak this fundamental kinetic principle into consideration when evaluat the acid- or alkaline-production potential of the rock section. A severe error is introduced when the potential of a rock to produce acidity or alkalinity is calculated only from the weights of the mineralogic components present in the sample. The weight of one component is balanced against another to assess the excess or deficiency of acid or base material. The kinetics involved in generating the ionic species from the bulk mineralogic component a never considered.

In the absence of calcareous material, iron sulfides (FeS-FeS_2 upon exposure to the atmosphere, oxidize and produce soluble hydro iron sulfates. Natural waters flowing over the weathered surface dissolve those products, which hydrolize and produce strongly acid drainages with attendant high concentrations of sulfate and iron. is known as acid mine drainage. Contingent upon the pH of the sol and oxidation state of the irons, the drainage may be clear or hav characteristic red-yellow color. As the pH begins to rise, the ir hydroxides precipitate and form the "yellow-boy" commonly observed the streams and rivers of some coal mining areas. Oxygen initiate

catalyzing bacteria in the natural environment is controlled by the presence of calcareous material, since the presence of carbonate tends to generate alkaline waters which inhibit the viability of the microorganisms.

Variations in pyrite morphology and crystallography significantly affect the rate of pyrite oxidation. Differences in acid production from strata of similar sulfur contents (and presumably similar pyrite contents) can be explained by variations in pyrite morphology: finer grained ($< 0.25\ \mu$) pyrite oxidizes more rapidly than do the coarse-grained ($> 50\ \mu$) particles.

The quality (acid, alkaline, or neutral) of coal mine drainage or leachate is determined by the proportions of alkaline- and acid-producing components present within the rock section of the mine site. This in turn can be related to the carbonate and sulfide content of the rocks.

Variations in mineralogy may affect drainage quality in several ways: at one extreme, the sequence of rocks in a mine may contain abundant carbonate material and minor amounts of pyrite, most of which is coarse grained. In this geologic setting, the natural aqueous regime will be alkaline and will have a high pH. The alkalinity and the high pH combine to restrict the activity of the catalyzing bacteria and to stabilize the pyrite present. Minor amounts of acidity (in the absence of catalyzing bacteria) produced by the coarse-grained pyrite are readily neutralized by the available alkalinity. Under those conditions, drainages from mines will be moderately alkaline, contain minor concentrations of sulfate and iron, and have moderate levels of total dissolved solids. In contrast, a paucity of carbonate material in geologic settings causes the pH of the natural water to be depressed below 5 by the carbonic acid reactions. In such a geochemical regime, the iron bacteria are active and available for the bacterial catalysis of the chemical reactions discussed above. Should the exposed rocks contain abundant fine-grained pyrite, rapid oxidation of the pyrite would occur and create acidic waters that would enhance the further dissolution of the sulfides. The combination of fine-grained pyrite, the absence of a neutralizing medium, a low pH, and the presence of iron bacteria catalysis produces a strongly acidic drainage that contains high levels of sulfate, iron, and dissolved solids.

Between these two end members of geology and geochemistry, and couched within the possible interplay of hydrologic variations, a variety of mine drainage chemistries is possible with different ranges of sulfate, acidity, iron, and alkalinity. In some areas, a unique set of geologic and hydrologic conditions may create special site-specific problems. In the Illinois (Eastern interior coal region) and Pocahontas (Appalachian coal region) coal basins, for example, highly saline layers are occasionally encountered that produce mine drainages with abnormally high concentrations of sodium, potassium, calcium, magnesium, and chloride. Some of the saline waters are produced by salt deposits occurring in the stratigraphic section; others are purported to be connate water (water trapped within the sedimentary section at the time the sediments were deposited). Similarly, beds of gypsum and anhydrite contained within the overburden of some coal mines

may produce hard, high-sulfate mine drainages having extremely high total dissolved solids. This problem most commonly occurs in the Gulf Coast Province.

Accelerated rock-acid water interactions, resulting from the formation of acidic drainages and lower pH, enhance the chemical decomposition of clays and silicate minerals. In addition to the acidity and the variety of chemical species found with the acid-producing reactions, other elements occurring within the coal and rocks are released from the host material and mobilized by the acidic drainages.

Increased concentrations of major elements (greater than 0.1 percent) such as silica, sodium, aluminum, calcium, iron, magnesium, manganese, copper, and zinc are associated with acidic mine drainages. Because of the depressed pH, the solubility of most of the common minor and trace elements is enhanced and entrained with the mine water. Elements (such as antimony, arsenic, barium, beryllium, boron, cadmium, chromium, lead, selenium, and zinc) are mobilized and redistributed within the hydro-geochemical environment affected by the mining process. The elements are mobilized and dispersed only if they remain in solution, become complexed, or are agglomerated with colloidal or suspended material. Elements in solution will continue to be dispersed as long as the flow path carrying the elements remains acidic. A rise in pH will cause decreases in solubility and element concentration.

Complexes of major, minor, and trace elements associated with suspended colloids or particulate matter will move with the flow path as turbidity. An effective filter is necessary to remove the suspended matter and associated elements from the water.

Elements occurring in coal mine drainages have a variety of sources. Coals tend to have concentrations of antimony, arsenic, boron, barium, and selenium and to have local enrichments of cadmium and zinc; however, most of these occur in coals in quantities less than in their crustal abundances. In shale and clay components, higher concentrations of other elements may occur and form the source for another set of accessory elements.

The mining method, the geology of the coal seam, and the manner in which the geochemical systems are disturbed determine the variety and set of elemental sources that will be released to the environment. An underground mine, which disturbs primarily the coal seam, will release a different combination and concentration of accessory elements than will a surface mine that disrupts the total rock section overlying the coal.

In addition, certain elements have a preferred association with either the organic, sulfide, or mineral phase; the association also affects the manner of release and the pathway of element transport from the mine site. Elements such as germanium, boron, and beryllium tend to be complexed within the organic constituents of coal. As a result, the elements will be physically transported from the mine site with the extracted coal. On the other hand, if cadmium, copper, lead, and zinc, which are known to have sulfide phases associated with the coal, become oxidized at the mine site, they will become soluble and can enter the

Dominating all the mechanisms, however, is the leaching and chemical decomposition of the mineral phases by acid water. Under strongly acidic conditions, most elements are leached from the host rock and introduced into the mine drainage. When that occurs, the character of the acid mine drainage takes on a different dimension, and the environmental impact goes beyond one of acid, sulfate, and iron pollution.

Chemical Effects in the West

For the West, two types of hydrogeochemical systems are considered: (1) systems that become acidic as a result of pyrite oxidation, and (2) systems in which acid production, if it occurs, is neutralized as a result of the presence of calcite or dolomite in the overburden. Both types exist in the eastern United States but, with minor exceptions, only the second type has been identified in the West. In the West, where surface mining has potential to cause an increase in the dissolved solids of ground water but where significant pH decline is a rarity, the dominant change in dissolved solids is due to an increase in sulfate salts of calcium, magnesium, and sodium (i.e., SO_4^{2-} increases are accompanied by increases in one or more of the three cations). Questions can be raised as to what level the increases can proceed and over what areas the water of increased concentrations can spread. In areas where Ca^{2+} is the dominant cation, the level to which Ca_2^+ and SO_4^{2-} can rise is limited by the solubility of the mineral gypsum ($CaSO_4 \cdot 2H_2O$). In the absence of major concentrations of other cations and anions, the solubility constraint will limit SO_4^{2-} concentrations to less than 2,000 mg/l and Ca^{2+} concentrations to less than 600 mg/l. The total dissolved solids in the water will generally contain less than 3,000 to 3,500 mg/l, and the water will therefore be slightly brackish. Because of the high SO_4^{2-} content, such water will be unfit for human consumption or livestock use. Compared to natural ground water in many parts of the western United States, the concentrations are not particularly high and, in some areas, are lower than regional values. It is not uncommon for natural ground water to be saturated or near saturation with gypsum. In the Fort Union coal region, gypsum is commonly observed in overburden of bedrock and glacial types, and therefore, sulfate occurs naturally in the ground water.

In areas where the overburden deposits contain clay minerals and abundant exchangeable Na^+ or Mg^{2+}, the Ca^{2+} concentrations in ground water are commonly much lower than would otherwise be the case because of the effect of cation exchange. The removal of Ca^{2+} by ion exchange enables the SO_4^{2-} content of the water to rise to higher levels because of the shift in status of the gypsum solubility constraint. In the West, sulfate values as high as 5,000 to 10,000 mg/l are observed in ground water affected by coal mining and, in some areas, in natural ground water. Even in those circumstances, the total

which is less than one-third of the dissolved solids in ocean water and generally less than a factor of 5 above the dissolved solids in natural ground water in many parts of the region. A change of this magnitude is smaller than the changes in shallow ground-water quality that have occurred in some parts of the southwestern United States as a result of irrigation.

In areas in which surface mining and land reclamation have occurred, the zone in which sulfate-rich water is most likely to develop is the ground-water zone within the backfilled material in the mined area. In many cases, the sulfate levels and total dissolved solids will exceed the levels that existed in the same depth zone prior to mining. When evaluating the significance of this potential for change in the quality of ground water, consideration must be given to the potential (1) for provision of alternative water supplies by acquisition of natural good-quality water from deeper ground-water zones in the area; (2) for downward migration of the high-sulfate, mining-affected water into zones that have water resource value; (3) for lateral migration of the high-sulfate, mining-affected water into zones that have water resource value; and (4) for seepage of the mining-affected water into streams, rivers, or other surface-water systems. In some hydrogeological settings, deeper zones for water supply are available. If significant downward seepage of high-sulfate water is not possible, the deeper zones may serve as the long-term water supply for domestic or agricultural use. In other situations, the shallow zone may have been the only significant source of potable ground water prior to mining and, therefore, its loss would greatly affect the potential for returning of the land to normal uses.

Lateral seepage of high-sulfate water from mining-affected land into streams, rivers, or lakes can result in changes in the water quality of the surface-water systems. The changes can range from those that are barely detectable to situations where the inflow of contaminated ground water exerts a major influence on the quality of the surface water. In the West, where surface water in some areas is naturally brackish, the influence of the ground-water seepage from mined land may have little or no influence on surface-water use.

A major factor in the potential for mining to influence water resources is the extent to which mining occurs in a given watershed. A single mine covering only a small area may not significantly degrade the water resources of a watershed, but several mines may.

Similarities between the effects of surface mining for coal and the effects of dry-land farming on ground water in the northern part of the Great Plains Province are of particular interest. In that region, the two activities are the main causes of landscape changes; they are in direct competition for the use of land, and the changes in water quality caused by each are results of the same hydrologic processes. In parts of western North Dakota and in Montana, the salinity and nitrate content of shallow ground water are dramatically increasing as a result of dry-land tillage of soil areas. The crop-fallow rotation system is particularly effective in changing ground-water quality. Under natural prairie grass cover, infiltration rates are relatively low, and the transportation of salt with ground water is relatively

slow. Conversion of the grasslands to fallowed land allows increased water recharge to shallow ground-water systems. The waters immediately encounter highly soluble salts that are copiously present in Northern Great Plains geologic materials, and the salts are transported through the ground-water systems. Dissolved-solids concentrations in the ground water are commonly as high as 25,000 mg/l and sometimes exceed that of seawater (35,000 mg/l). The principal salts are sodium, magnesium, and sulfate, but toxic trace elements such as selenium have also been found in dangerous concentrations (Donovan and others 1979). The effects, most common in ground-water systems that are shallow and local, are evidenced by discharged ground water saline enough to kill vegetation and destroy soil structure. The areas of the discharges are nearly devoid of vegetation, are covered with white veneers of salts, and are commonly waterlogged by the excessive and continuous discharge of ground water. Commonly called "saline seeps," the areas are matters of deep concern because an increasing number of acres are becoming nonproductive. In Montana, more than 140,000 acres have thus far been affected, and the acreage is increasing by an estimated 10,000 acres per year (Miller and others 1976). In North Dakota, between 50,000 and 100,000 acres are estimated to be affected. In South Dakota, 14 counties have thus far been affected but the amount of land has not been estimated. In Alberta, Canada, the estimated area affected by saline seep totals 250,000 acres. Impacts of the problem have thus far been judged by the removal of agricultural lands from production; off-site impacts on ground-water supplies and fish and wildlife resources are not yet clear.

In comparison, less than 20,000 acres of land in Montana and North Dakota (combined) have been surface mined. It might be assumed that the sulfate salt content of spoil water in about half of the total mined area has or will increase above pre-mining levels.

Increases in sulfate salts in shallow ground water in Montana and North Dakota are occurring or will occur on an appreciable scale as a result of soil tillage and of surface mining of coal. When considering the general impacts of mining on ground water in the region, soil tillage as a major cause of increases in sulfate salt must also be taken into account.

In summary, one of the potential environmental effects of surface mining in the Northern Great Plains Province is the gradual creation of saline soil as a result of changes in the quality of subsurface water. Whether or not mining will cause appreciable salinization of soil in reclaimed areas or in adjacent land in the West has not been established. The loss of productive agricultural land as a result of salinization is already a severe problem in parts of North Dakota and Montana. The spread of saline soil has been caused by agricultural activities such as tillage and cropping of the land and the disruption of the natural drainage systems by road networks. Each year acres of productive land are lost by invasion of salt into the soil. Salinization resulting from mining may add to this figure, but whether or not mining activities will be significant remains to be determined. In some areas, reclaimed land may be less susceptible to salinization than premined land.

REPRESENTATIVE SETTINGS

The relationship between topography, coal-seam occurrence, and ground water can be depicted in idealized cross-sections of the subsurface environment. Such diagrams represent the potential geologic conditions that might be present in the major coal regions of the United States and provide a framework for discussing variable effects upon ground-water systems.

Figures 4.4 and 4.5 illustrate the representative geologic settings. The location of a surface mine at the various points shown in Figure 4.4 would affect the ground-water system in different ways. First, ground water flowing to stream Y is separate from that flowing to stream X above the confluence of the two streams. A mine at location A would affect the ground-water system to the west of stream Y but not to the east of the stream (Figure 4.4a). A mine at location B would affect only the ground water flowing to stream X because the site is located down-gradient from the recharge zone (Figure 4.4b). The ground water on the southeast site of stream X would not be affected. For a mine located at location C, which is on the divide between two basins and the recharge zone for those basins, the effect is much greater. The contamination enclave could move into both basins but, more important, will penetrate deeper into the ground-water system. (Figure 4.4c).

The overall scale represented by the diagrams may vary. As an example, a mine has been located in Setting A (Figure 4.5a) to indicate the relative scale. The pit may be as much as 1 mile in length and 150 ft. across, and the depths may reach 120 ft. Geologic materials have been generalized into single units representing many beds or layers of rock. Setting A (Figure 4.5a) represents horizontal, single or multiple seams of coal that have relatively thin soil cover. The rocks between coal seams are shale, siltstone, and sandstone, in varying thicknesses. Coal seams can be thin (3 to 10 ft.) or thick (greater than 10 ft.). In the East, the seams are thin; in the West, they tend to be thick. The position of the water tables shown for each setting depends on the climatic conditions of a region; i.e., in western arid to semi-arid environments, only the lower water table may represent the condition of saturation, whereas in the East, the upper water-table position would be more realistic.

Setting B (Figure 4.5b) represents horizontal, single or multiple coal seams overlain by thick unconsolidated material, which in turn overlies bedrock. The unconsolidated material may include alluvial sediments, and any one of the water-table positions shown may exist. Setting C (Figure 4.5c) represents dipping coal seams, either single or multiple, with the water-table position a function of climate. The seam dips toward the valley. Setting D (Figure 4.5d) is similar except that the seams dip into the hillside and away from the valley. In Setting E (Figure 4.5e), single or multiple seams are interbedded in unconsolidated materials. The degree of saturation is represented by the water-table positions.

Each of the diagrams represents only part of a ground-water system. A mine may occur within a single surface-drainage basin or

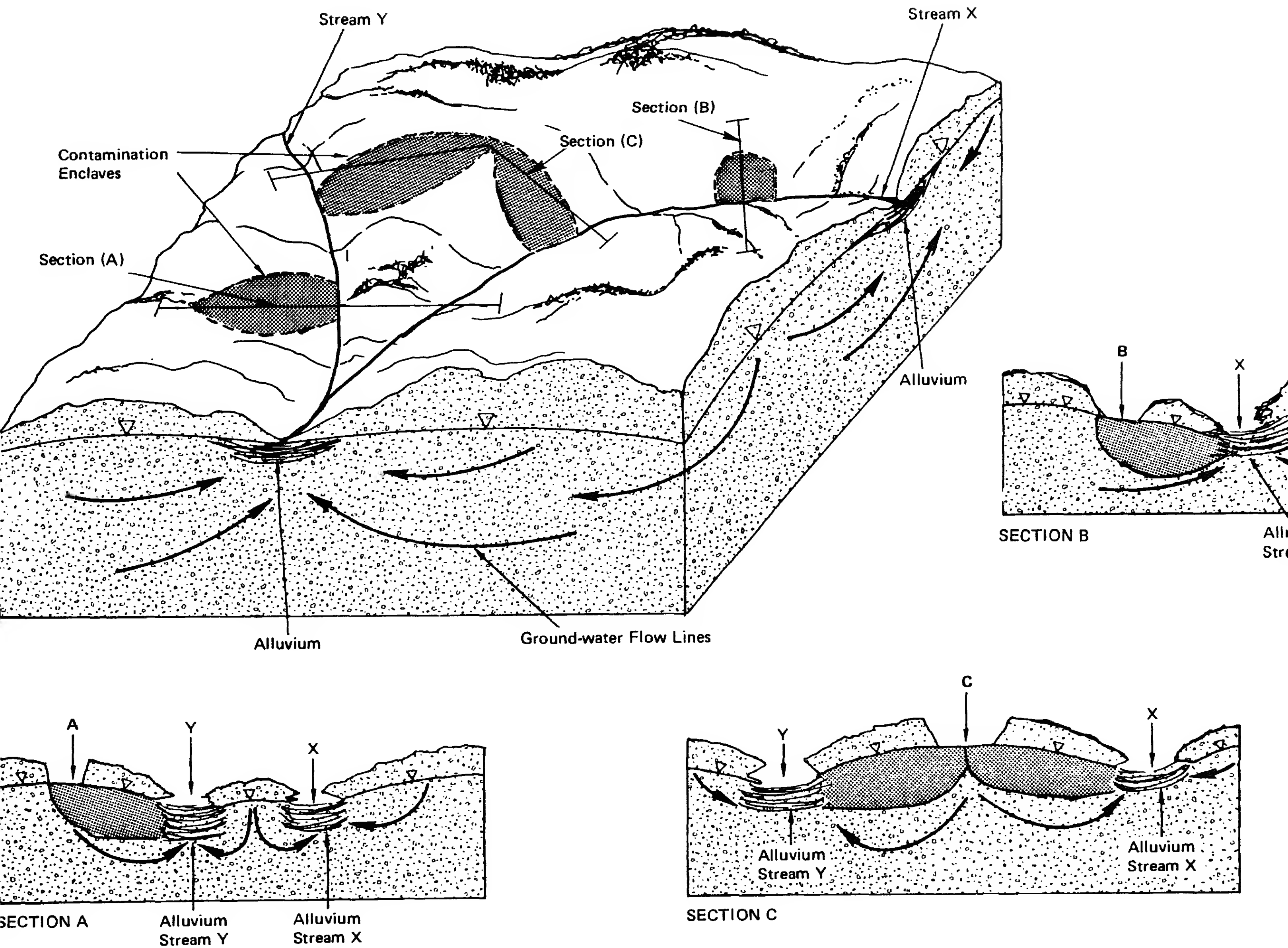


FIGURE 4.4 Hypothetical Relationship Between the Location of a Surface Mine and a Regional Ground-Water Flow System. A, B, and C = Mine Locations.

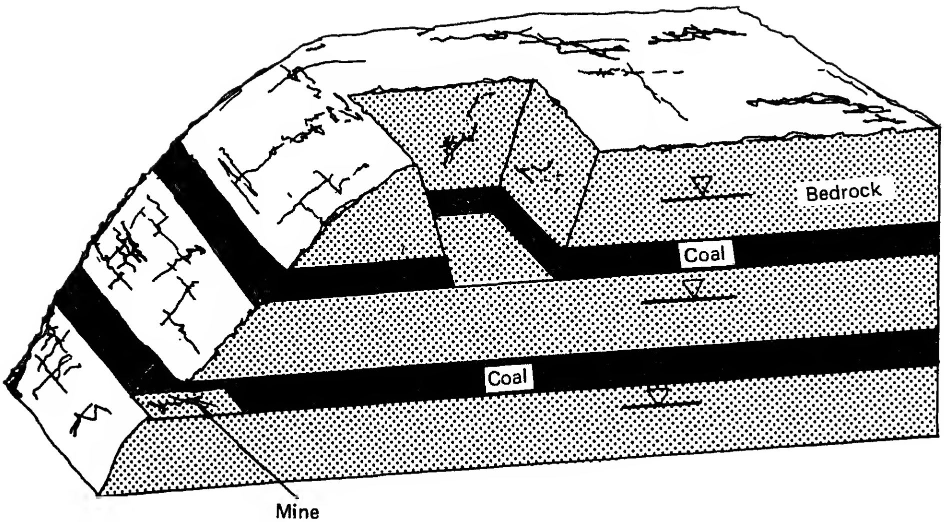


FIGURE 4.5a Representative Geologic Setting A

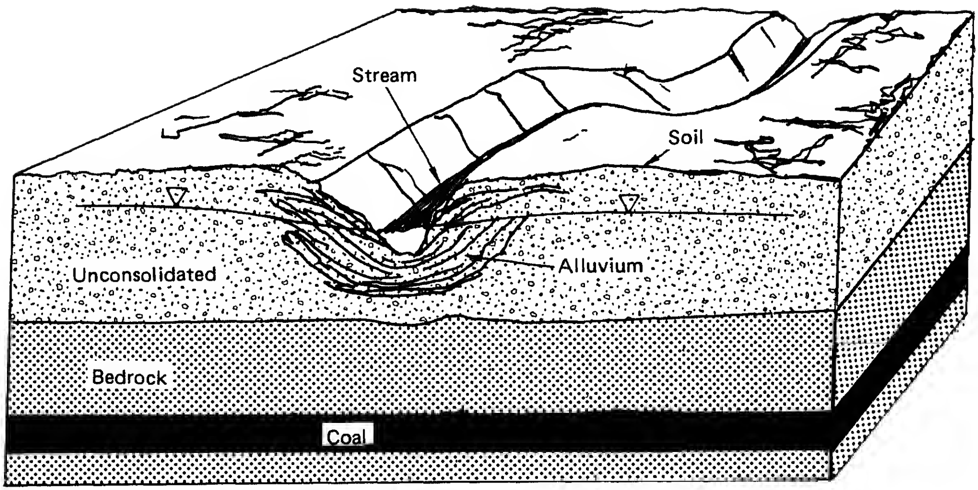


FIGURE 4.5b Representative Geologic Setting B

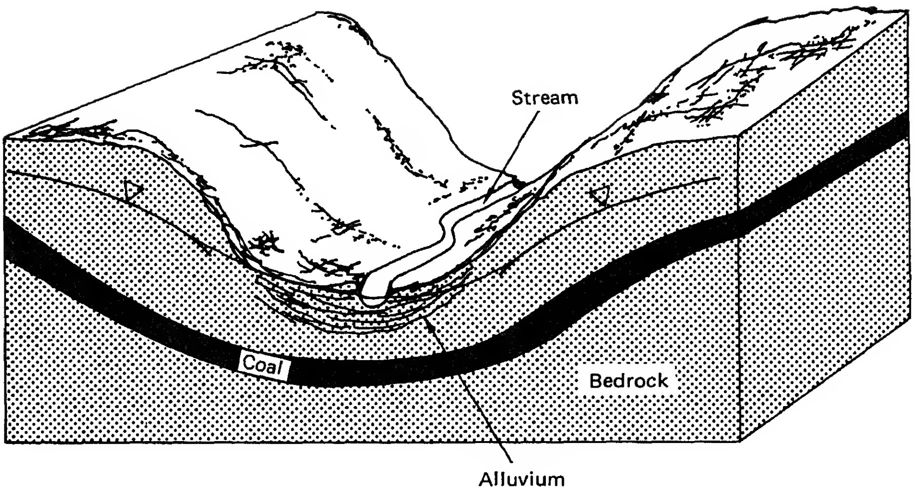


FIGURE 4.5c Representative Geologic Setting C

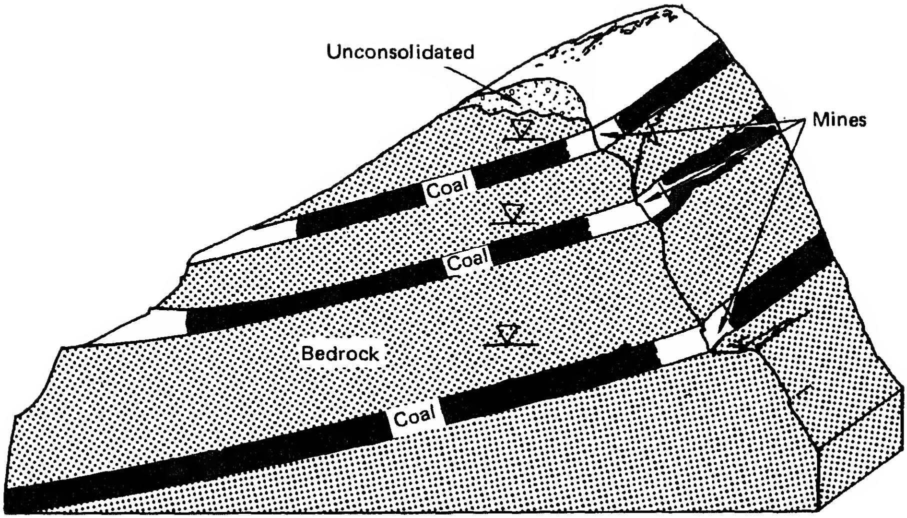


FIGURE 4.5d Representative Geologic Setting D

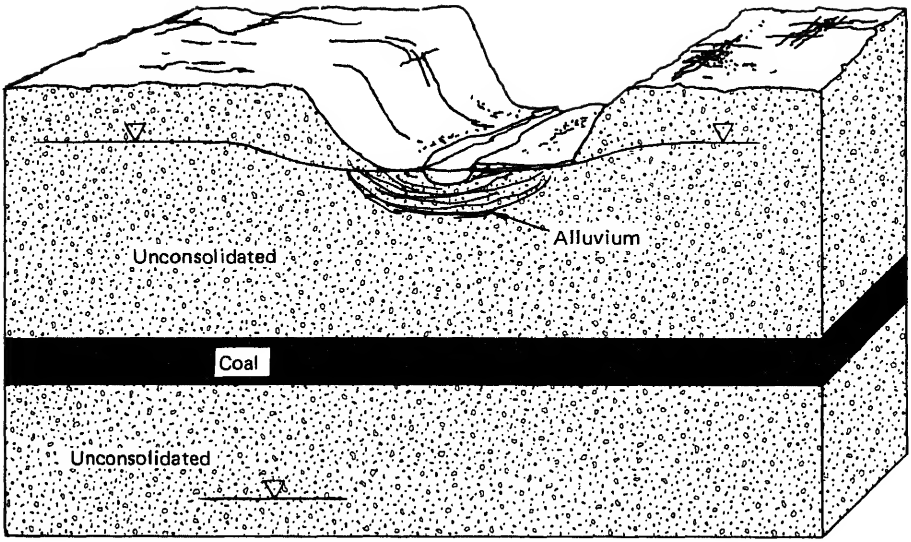


FIGURE 4.5e Representative Geologic Setting E

several basins, as indicated by Figure 4.4. This factor may control the ground-water flow system and introduce a complex situation where more than one flow system is involved. For the purposes of this discussion, only one part of a flow system is depicted.

Effects on ground water are both physical and chemical. In the following sections, the potential settings in relation to predicted effects from different mining methods are described. The discussion relates hydrology, topography, and geology to the potential mining methods that can be employed.

PHYSICAL EFFECTS OF MINING WITHIN REPRESENTATIVE SETTINGS

Representative Setting A (Figure 4.5a)

Area and Contour Mining

Mines in Setting A are located below the water table, and the mining zones above the coal seam are initially dewatered during the mining process. The highwall will intercept local aquifers and cause partial dewatering of adjacent lands. Following completion of the mining phase and backfilling of the mine site, ground water will become recharged and, with time, a ground-water mound and re-establishment of the water table may take place, contingent upon the permeability of the backfilled mine.

The ground-water regime below the seam will not be affected if water-table conditions exist. However, if artesian conditions exist, which may be common in the West, and if the underclay is fractured, partial dewatering of the subjacent aquifier may occur during mining. On a long-term basis, however, after a mine is backfilled, dewatering becomes less dominant as the near-surface ground-water regime becomes re-established in the backfilled mine. As long as the underclay remains intact, little, if any, hydraulic interconnection of the ground-water regimes will occur above and below the underclay, and the mining effect on the underlying ground-water system will be minimized.

In western geologic settings, the water table may occur at any of the positions shown if the site is located in a high-relief area. However, if the relief is low, the water table would be found at the lower position. Strata between the aquifers are mostly beds of clay and silt, the predominant materials in the West. They effectively restrict recharge when exposed at land surface and effectively restrict vertical flow in the subsurface. For western mines other than those in Washington State, evapotranspiration ranges areally from about 30 in. per year to about 60 in. per year. Average annual precipitation ranges areally from less than 10 in. to about 20 in. Recharge to the ground-water systems can occur, therefore, only under select conditions.

Discharge of ground water often occurs inconspicuously along outcrops, where flow rates are less than the demands of evapotranspiration. At the land surface in those areas, little evidence of ground water can be seen, although changes in type or vigor

geologic and topographic conditions are such that discharging ground water is concentrated at springs, which are highly valued in the West as water sources for livestock and domestic uses.

Other Types of Mining

The coal seams in Setting A could be reached by slope, drift, or vertical shaft mines. However, those types of mining are discussed more appropriately in the following representative settings.

Representative Setting B (Figure 4.5b)

Setting B is similar to Setting A, except that entry to the coal seam cannot be along the edge of the outcrop.

Underground Mining/Slope and Vertical Shaft Mines

Mine entries in slope and vertical shaft mining will dewater the strata immediately above the mine opening, depending on the nature and permeability of the roof rock and the hydraulic properties of the confining strata. Obviously, the mines must be kept dry during the mining phase and thus, provide a constant ground-water sink. After mining and pumping cease, however, the mine may flood, and the ground-water system will re-establish in the zones above the coal seams. If abundant roof collapse occurs, contingent upon the thickness of the overlying beds, fractures will propagate upward (in some cases, all the way to the ground surface), thereby increasing the degree of hydraulic interconnection with the strata overlying the abandoned mine. In mines with multiple-seam entries, closer vertical spacing leads to a greater degree of hydraulic connection. Eventually, the area will stabilize and the ground-water flow system will be re-established in a more permeable fractured system. This hydraulic communication between seams can become a hazard and can act as an avenue for contamination of deeper ground-water systems.

Area Mining

Area mining occurs most often in Setting B. The discussion under Setting A is applicable, except that Setting B involves alluvial valleys. The valleys can be important water reservoirs, depending on their size, thickness, aquifer characteristics, and availability of water.

In some parts of the United States, geologically younger unconsolidated deposits cover consolidated bedrock containing coal.

renders them more permeable than the underlying bedrock and effectively creates a multilevel aquifer system. The thickness of the deposits also varies, and the thicker zones may serve as domestic water supplies or as storage and recharge mechanisms for the underlying aquifers.

Surface mines cutting into highly permeable unconsolidated deposits will invariably encounter large volumes of water. Such mines in Setting B can dewater the aquifer and thus affect a relatively large area owing to the high hydraulic conductivities of the deposits. A mine that cuts into both the alluvium cap and the underlying bedrock will encounter numerous springs at the contact of the deposits. On a short-term basis, the unconsolidated material will yield large amounts of water and is readily recharged by local precipitation. Bedrock material, however, may have lower hydraulic conductivities; the mine cutting into bedrock will encounter smaller volumes of water. As a result, the dewatering of a mine in consolidated rock will not be so extensive, and such a mine will not readily respond to recharge events. If the hydraulic conductivities of the bedrock equal or exceed those of the alluvial aquifer, the situation is reversed. On a long-term basis following backfilling operations, ground-water recharge will take place and a water table and a ground-water flow system will be re-established.

In the West, the term alluvial valley floor has gained special recognition. Alluvial deposits occupy valleys of major watercourses. They are generally much more permeable than bedrock aquifers and, where irrigated naturally or manually, have great agricultural potential. Because the deposits occupy valley bottoms, they receive recharge from many sources, such as direct runoff from nearby bedrock aquifers, direct precipitation, return flow from irrigation, and stream flow from parent watercourses. Such deposits provide transient storage for water after periods of recharge, gradually discharging the stored water to streams during drier periods. In many alluvial deposits (particularly those along perennial streams), the water table lies so close to the land surface that vegetation is subirrigated. Where alluvium is recharged principally by ground water from other aquifers and where evapotranspiration is active, water in the alluvium often is of such poor quality that it is unusable.

Representative Setting C (Figure 4.5c)

Area and Contour Mining

In Setting C, the ground-water response on a long-term basis is similar to that discussed under Setting B. On a short-term basis, however, the ground-water situation is radically different. From a regional standpoint, the setting is a ground-water discharge area and

bottom lands, still intercept the regional flow system and drain the aquifers above the coals.

Unless the aquifer below the coal seam is confined, surface mines should have no effect on the ground water located beneath the coal, as long as the underclay remains intact and is laterally continuous beneath the mine floor.

Underground Mining

Any underground mine located within the valley of Setting C will behave as a large-diameter well. Fractures developing in the roof material will enhance vertical movement of water from the overlying strata. The mine walls will intercept lateral flow and, because of the regional setting, the hydraulic gradients driving the ground water into the mine face are greater than those expected in Settings A and B.

On a short-term basis, strata overlying the coal will be dewatered in response to mine location and efforts to prevent inundation of the mine. In multiple-seam entry mines, vertical interconnection may be enhanced, and a greater degree of vertical dewatering encountered. Following mine closure and cessation of pumping, underground mines in Setting C will generally flood more quickly, and the ground-water flow system will become re-established sooner than in any other geologic settings.

As in other cases, if the underclay below the mine floor remains intact and is continuous throughout the mined area, the ground-water flow system in strata below the mine should not be radically affected. However, if the ground water below the mine is in an artesian (confined) state and the hydraulic integrity of the underclay is breached, the aquifer will be partially dewatered by the overlying mine. As in other cases where advanced flooding of the mined zone occurs, the ground-water flow system will become re-established and, therefore, the negative impact of the mine on the ground-water regime will lessen over time.

Representative Setting D (Figure 4.5d)

Setting D may be unrealistic in scale, in that it is shown as a mountain; nevertheless, it illustrates several of the variables present in highly folded rocks.

Drift Mining

Fundamentally, the impact of a drift mine that originates at the side of a hill along the coal outcrop will be about the same as that discussed in Setting C. The main difference is the direction in which the mine slopes (or dips) with respect to the mine opening. If the seam dips toward the mine opening, the flow system affected by the mine will be dewatered continuously by gravity drainage, unless the entry is

and all strata above the coal seam may be partially dewatered. With continual roof collapse and overburden fracturing, hydraulic continuity is increased and dewatering is enhanced.

On the other hand, mines that follow seams dipping away from the mine opening will cause dewatering of the overlying strata on a short-term basis. However, with time, the mine opening will flood (the water having no ready discharge outlet), and the ground-water system will become re-established, providing there are no drainage outlets or integrating flow paths. Drainage outlets may be natural or manmade (such as abandoned oil wells or mine shafts previously used for power or ventilation).

Area or Contour Mining

Area or contour mines in Setting D will cause partial dewatering in local areas on a short-term basis. As mining progresses along the coal seam, an increasingly greater thickness of overburden is exposed and a wider mine floor created. Mining will progress until the overburden-to-coal thickness ratio becomes too great to make the mine operation economical. At that point, augering may take place, which will increase the permeability of the coal seam.

During backfilling, a local ground-water system will be established from the down-dip area upward to the land surface. Owing to the more porous and permeable nature of backfill material, local ground-water gradients will be more readily established in mine openings than in surrounding undisturbed rock. The major difference between the two is that the stratification of the undisturbed rock will continue to allow lateral movement of water. The random orientation of the fill material will not induce preferential ground-water movement that will respond to local hydraulic gradients, and, in some cases, a reversal in the original flow direction will take place in the backfill material and adjacent areas.

In some area mining operations (such as mountaintop removal), backfilling proceeds at the same rate as the mining process. In those situations, the ground-water system will continually enlarge with backfill operations, and a new ground-water regime will constantly be reformed. Where contour mining operations defer backfilling until mining is completed, the water table will eventually be re-established over the entire area in response to recharge.

Other Mining Methods

The effects of other underground mining methods applicable to this setting have been described in Settings C and D.

Representative Setting E (Figure 4.5e)

Area Mining

In this geologic setting, the sedimentary material above a
the coal seam is unconsolidated to semiconsolidated. Because
may be composed primarily of lignite to subbituminous coal, un
that would normally control the vertical movement of ground wa
or may not be present. In such an area, a greater degree of h
interconnection would be expected and mines will dewater large
In general, the hydraulic system below the coal seam should no
affected by the surface coal mine.

Other Mining Methods

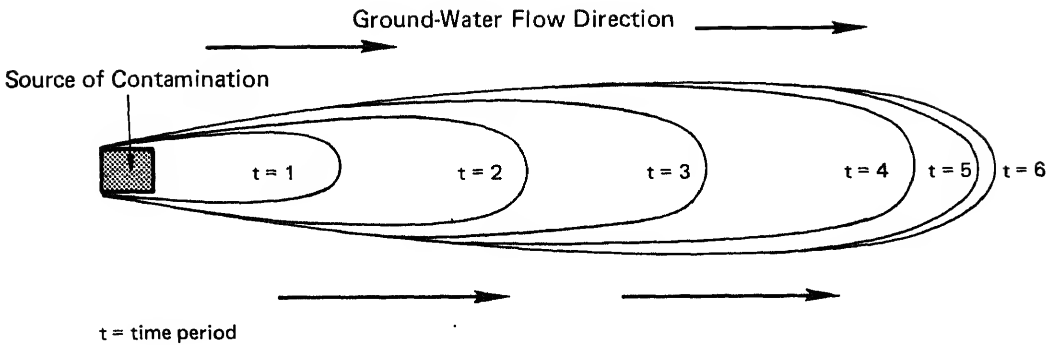
Underground mining is not applicable in Setting E.

CHEMICAL EFFECTS OF MINING WITHIN REPRESENTATIVE SETTI

The chemical effects within any single setting vary greatl
thus, cannot be related to each type setting. However, the na
the contamination enclave that will emanate from a mining site
described.

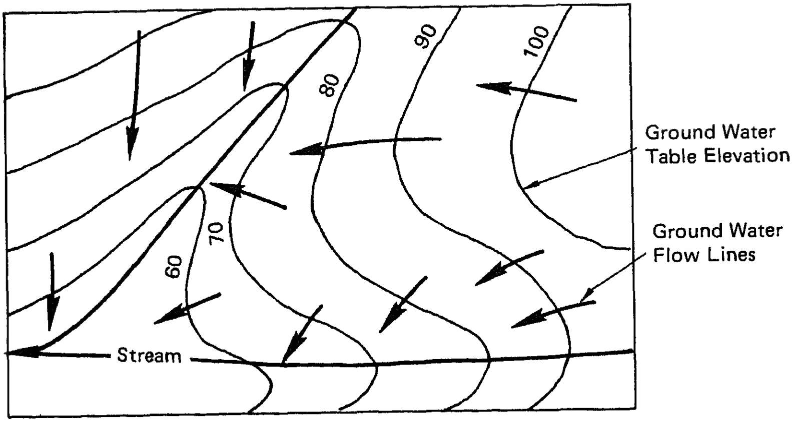
A contamination enclave develops when chemical changes occ
given site and the ground water moving past the point of conta
is altered. Thus, the contamination enclave is a body of grou
that has a chemical composition different from the surrounding
water. The enclave is a three-dimensional body that varies in
within the ground-water system owing to dilution and to differ
of transport of different chemical constitutents related to ge
processes such as adsorption and reduction. An enclave will g
size that will be controlled by truncation at a ground-water s
as a stream) or that will extend to an equilibrium condition w
surrounding water on the down-gradient end dilutes the enclave
such a degree that it is not different from the surrounding wa
(Figure 4.6). For all practical purposes, the enclave follows
ground-water flow line even though it may be of a slightly hig
density. For Representative Settings A, B, C, and E, Figures
and 4.4 illustrate the shape of the contamination enclave that
develop.

The chemical composition of the enclave is a function of t
of transportation of each element within the ground-water flow
Because some elements travel faster than others, the enclave h
zonation. No reported cases of zonation have been documented

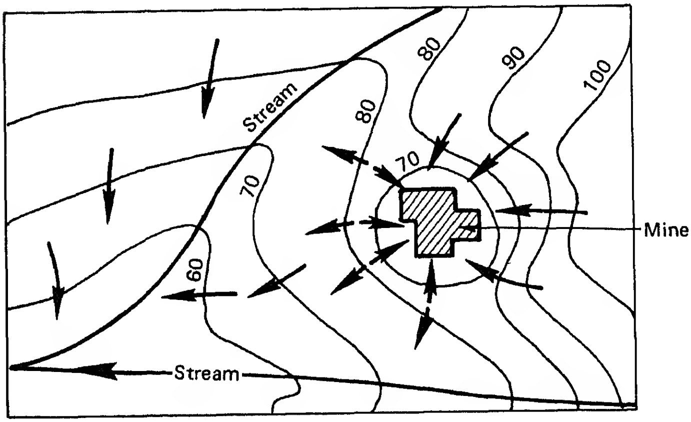


SOURCE: Palmquist and Sendlein, 1975.

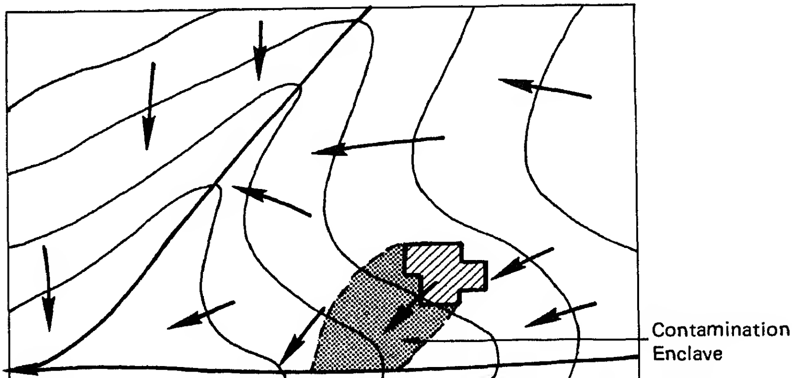
FIGURE 4.6 The Growth of Contamination Enclaves Through Time

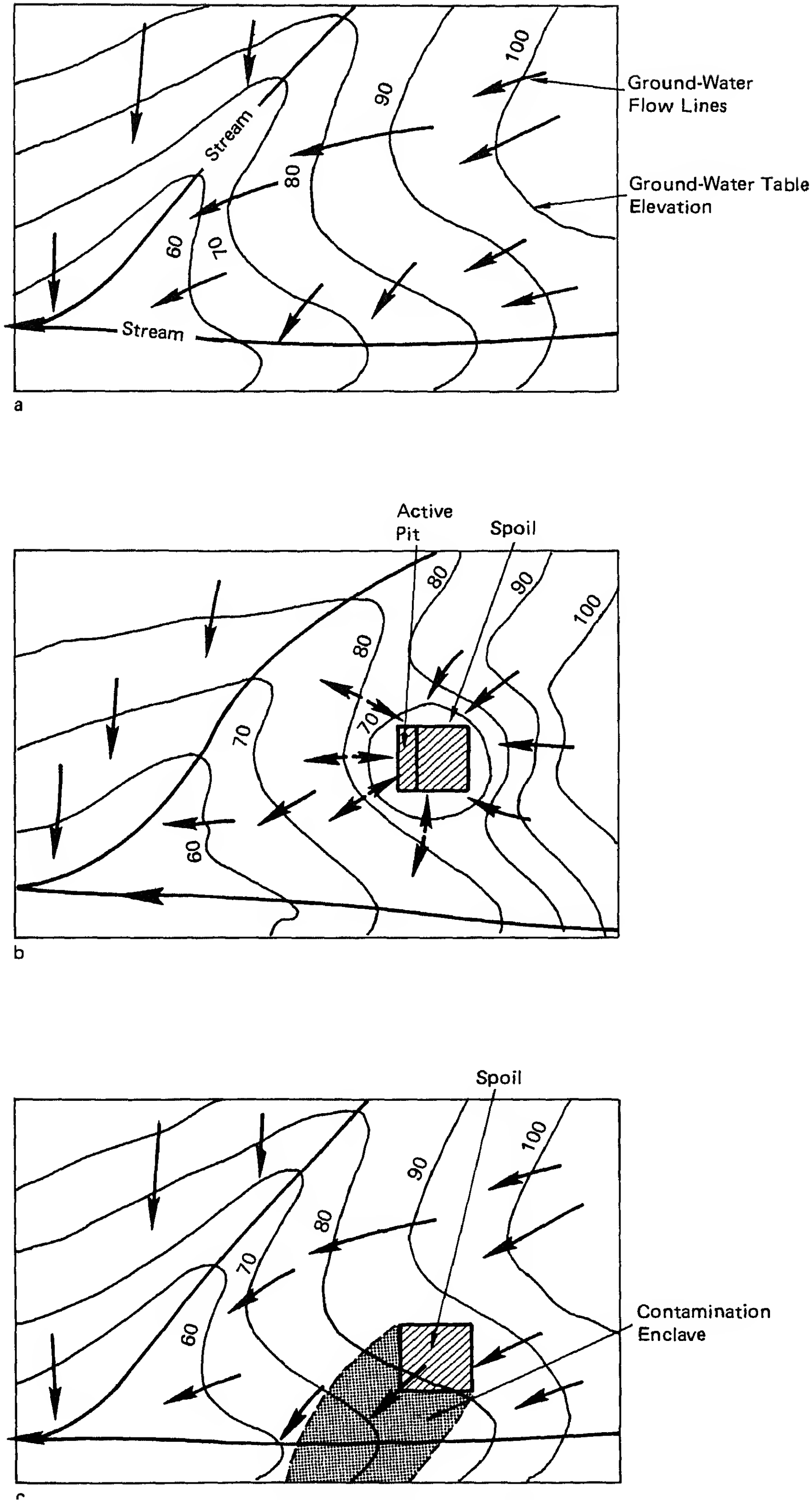

90
100
80
70
60
Ground Water
Table Elevation
Ground Water
Flow Lines
Stream

a

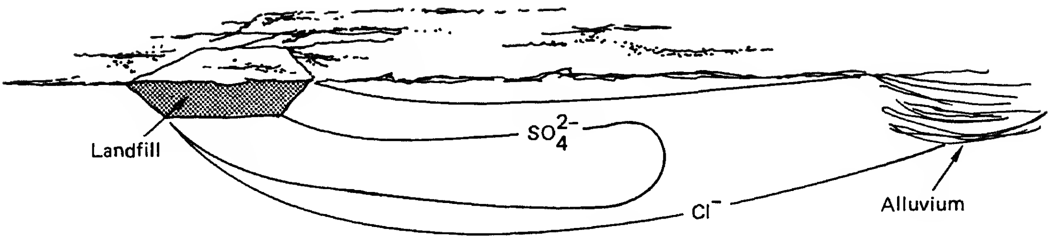

80
90
100
Stream
80
70
70
Mine
60
Stream

b


Contamination
Enclave



100
90
80
70
60
Stream
Stream
Ground-Water Flow Lines
Ground-Water Table Elevation
a
Active Pit
Spoil
80
90
100
80
70
70
60
b
Spoil
100
90
80
70
60
Contamination Enclave



SOURCE: Palmquist and Sendlein, 1975.

FIGURE 4.9 Configuration of a Contamination Enclave from a Landfill

Surface Mines

In surface mines, large volumes of overburden are commonly excavated from above the coal seam(s) in order for the coal to be removed. The stripped overburden (spoil) provides exposure of large particulate surface areas to water that infiltrates through the spoil piles located on the ground surface or through the backfill in previously mined areas. Much of the spoil has not previously been exposed to the processes of active weathering associated with infiltration. The intensity of weathering in the spoil is normally much greater than that which existed previously in the overburden in its natural state. The increased intensity is caused primarily by the presence of oxygen and water in the pore spaces of the spoil.

Normally, overburden in its natural state is covered by soil that supports vegetation and that contains, in its upper layers, considerable organic matter. Primarily as a result of oxidation of organic matter, the soil zone consumes oxygen in water that infiltrates through the soil as well as oxygen that enters the soil from the atmosphere. In contrast, mine spoil is exposed to the atmosphere as the overburden is excavated and redeposited. In the redeposited state, the spoil has abundant pore spaces containing atmospheric oxygen. If the spoil contains reactive pyrite, oxidation of the pyrite can occur, with the pore water continually acquiring oxygen from the air in the pore spaces. Oxygen is only slightly soluble in water (9 to 11 mg/l), but if the pore water is in contact with a gas phase (i.e., partially saturated conditions above the water table) in the pores, the oxygen is continually transferred to the pore water as oxidation occurs. If the oxygen is replenished from the atmosphere, the process of oxidation can proceed relatively unabated, and the water that infiltrates through the spoil to the water table can continue to acquire high dissolved solids and, in the absence of carbonate minerals in the spoil, continue to be characterized by low pH.

In the reclamation process, a layer of topsoil is applied to the contoured spoil in a backfilled mine and the surface becomes revegetated. If the void spaces in the backfilled mine become isolated from the atmosphere, oxidation of pyrite in the spoil will diminish or cease as the initial oxygen in the void space is consumed. In the surface soil, as in natural soil, oxygen is consumed by oxidation of organic matter and CO_2 is produced. As CO_2 from the surface zone moves downward through the soil, the gas phase in the voids acquires higher CO_2 contents; this combined with a low concentration of O_2 may approach the pre-mining conditions of the geological materials. The time scale associated with the evolution of the hydrogeochemical phases may vary over years, decades, or possibly centuries and, with existing knowledge, cannot be predicted with much confidence.

A rising water table that inundates pyrite-rich zones in the spoil is another mechanism by which pyrite oxidation is inhibited. A fluctuating water table can promote weathering in the zone of fluctuation, but if no replenishment of oxygen from the atmosphere occurs, severe degradation of the quality of the ground water is

In situations where the spoil materials contain significant concentrations of soluble sulfate salts (i.e., sulfate is available simply by dissolution of sulfate minerals rather than sulfate generation by pyrite oxidation), the rise of the water table in the backfill material will result in increased sulfate and cation concentrations. As ground-water flow occurs, the soluble sulfate salts are flushed from the system and, if the initial sulfate salt content in the spoil is low, they will gradually be completely flushed out.

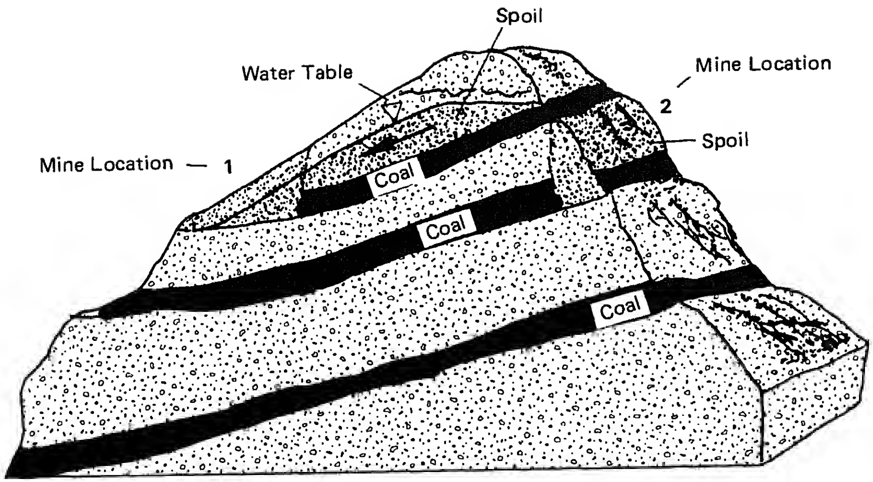
In some areas, surface-mine excavations have been used for disposal of fly ash, scrubber sludge and cleaning plant wastes that are buried at the bottom of or within the spoil. The wastes provide varying amounts of dissolved solids to the ground water, depending on the depth of burial, infiltration rate and occurrence, water table depth and fluctuation interval, and other factors. In some hydrogeologic settings, burial of fly ash or scrubber sludge in the mine pits can be accomplished with little or no effect on ground-water quality. In other settings, the buried waste can be the dominant influence on chemical change in the water.

This discussion of chemical effects can be applied to all of the representative settings; however, the nature and degree to which the water quality is altered are functions of the climate and the geologic materials disturbed. Representative Setting D (Figure 4.5d) presents different conditions. Because the setting potentially has more complex ground-water interactions, generalizations are difficult and enclaves that do develop probably would be small. As shown in Figure 4.10a, re-established ground water affected by a contour mine at location 1 would flow toward the valley wall and would emerge as a spring or series of seeps, putting the contaminated water on the surface. The same would occur for a mine at location 2 if the ground-water flow was toward the valley. However, if the ground-water flow was controlled by the dipping beds, an enclave would develop down the dip, would probably flow into the coal seam, and perhaps would find its way to the other side of the mountain.

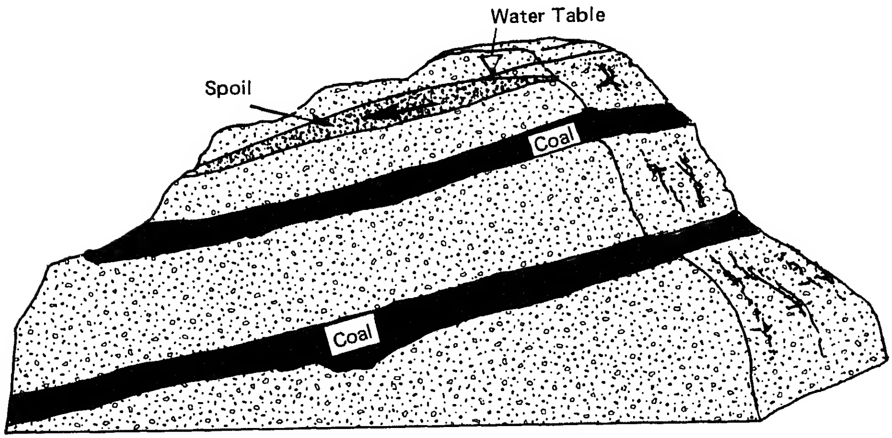
For mountaintop removal methods (Figure 4.10b), the ground water would re-establish itself and flow toward the valley and might produce contaminated water that would discharge or seep down the valley wall.

Underground Mines

Unlike surface mines that disrupt many varieties of rocks, underground mines generally penetrate coal seems and adjacent strata. The potential to produce acidity is greatest along the coal seam. During the mining phase, when the coal is exposed to the atmosphere and the mine is dewatered, oxidation processes are accelerated. Ground water draining into the mine dissolves oxidation products (which readily hydrolize in water) and produces acid. In most cases, the chemistry of natural water can be ignored when compared to the potential ionic strength of the mine drainage that will be produced. On a short-term basis, the exposed pyrite-containing mine faces continue to oxidize and generate acidic products. In mines here ro k



(a) Contour Mining Method



(b) Mountaintop Removal Method

FIGURE 4.10 Ground-Water Flow Within Contour Mining and Mountaintop Removal Methods

dusting with chemicals is routinely practiced, the quality of the drainage is radically affected by the material used to dust mine walls. If an alkaline material is used, it can probably offset the pyrite oxidation reaction and may produce alkaline mine drainages. However, when the dust is no longer present, the mine may become a long-term source of acid water.

Following the completion of the mine operation and abandonment of dewatering facilities, mine openings may flood or continue to dewater by gravity drainage. The oxidation reactions will become inhibited by inundation or continue to occur during dewatering. Roof collapse may occur where fractures propagate upward and intercept aquifers of different water chemistries. Thus, the quality of the drainage will be affected differently in the early phase of the mining operation in comparison to the end phase when the mine opening is abandoned. The problem is accentuated where multi-seam mining occurs and where poor and good quality water connect between coal seams.

Contamination resulting from underground mines typically is less significant than that from surface mines. The underground area affected is the coal seam and adjacent zones. In most coal mines, the coal seam is underlain by an underclay that will impede downward movement of water. Often, the coal seam is overlain by sandstone and siltstone that may have higher hydraulic conductivities and thus provide an additional path for contaminants to follow.

Figures 4.7c and 4.11 illustrate how a contamination enclave might appear after the mine is abandoned and after the regional ground-water flow system is established. The enclave boundaries will be controlled by hydraulic conductives and geochemical reactions rather than by dilution with surrounding water. The enclave will elongate in the direction parallel to ground-water flow. Figures 4.7c and 4.11 represent conditions that would be found in Representative Settings A, B, and C (Figures 4.5a, b, and c). For Representative Setting E, the materials above and below the coal are unconsolidated and the enclave therefore would be less constrained by the hydraulic conductivity boundary for the other settings. This would result in the enclave boundaries being determined by dilution and some boundary control. The condition is similar to the way enclave boundaries are formed as a result of surface mining.

Figure 4.12 addresses Representative Setting D (Figure 4.5), which is more complex. The manner in which the coal is entered (e.g., through a vertical shaft or a drift mine entry at the outcrop) will control to some extent how the contamination enclave develops. Sites 4 and 2 would develop an enclave much like that illustrated in Figure 4.11. Site 3 would probably produce acid drainage to the surface. Site 4 illustrates a complex contamination enclave that would develop along the coal seam being mined; owing to joints, the enclave could migrate downward to other aquifer zones. The sandstone shown in Figure 4.12 is one possible material through which the enclave could move faster and a second coal seam could be encountered. If the coal seam is not mined, the contaminated ground water will eventually move along the bed of the coal seam and discharge at the surface as acid runoff.

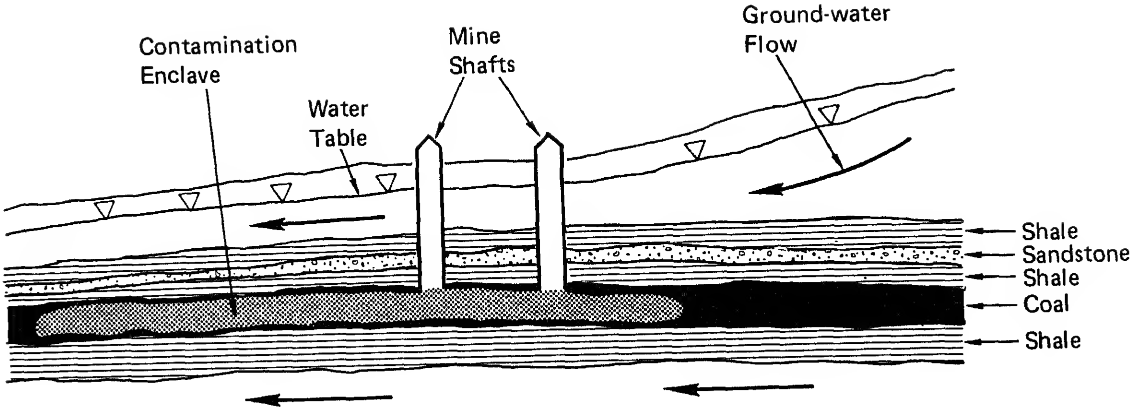


FIGURE 4.11 Formation of a Contamination Enclave

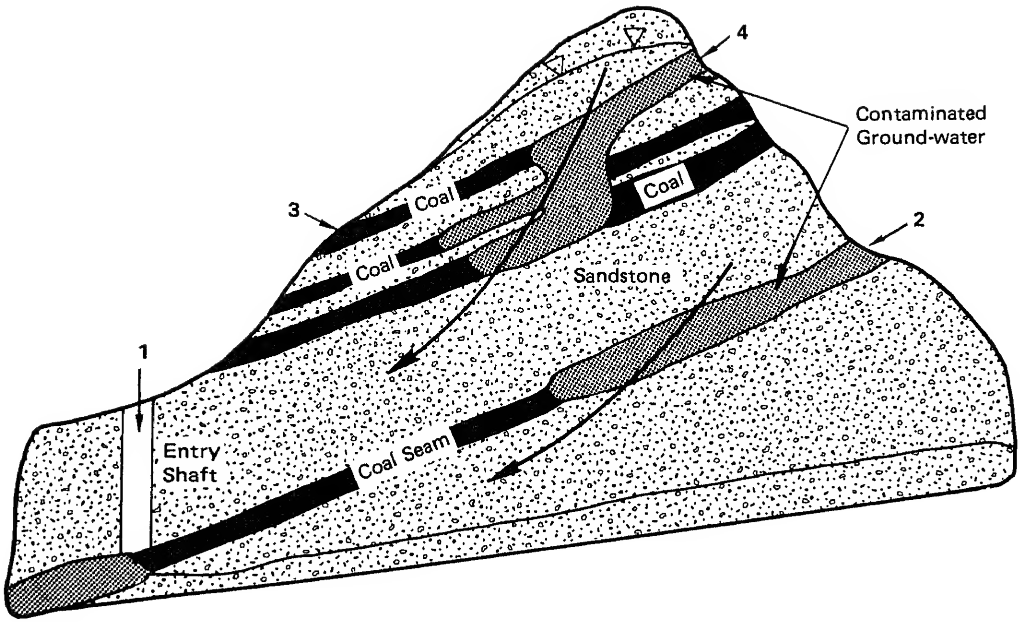


FIGURE 4.12 Effects of Multi-Seam Mining on Ground-Water Systems
1–4 = Mine Locations

Underground Coal Gasification

Current underground coal gasification, or in-situ mining, in the United States is experimental. The operations consequently are small in scale and designed to acquire knowledge about technological and environmental aspects of the underground coal gasification technology. Thus, explicit knowledge about a commercial-scale operation can only be hypothesized from the results of the experiments. However, data acquisitions and subsequent analyses of laboratory and field experiments are contributing to the general understanding of environmental changes.

The chemical kinetics of converting coal to gases and liquids results in thermal-stress cracking of the coal seam and surrounding rocks, production of ash (the majority of which remains underground) and tars, and changes in the mineralogy of affected rocks, as shown in Figure 4.13. The distribution of hydraulic rocks (the mechanical energy in the flow system) is changed by product extraction and injection of air under high pressure. As a result, the available space underground (porosity) increases and in turn increases the permeability of surrounding rocks. Increased permeability and the reduced distribution of hydraulic head in the gas generation process results in water influx to the gas generators. It also reduces the heating value of the product gas and changes the direction and ratio of ground-water flow which, depending on the relative scale of operation, may cause changes in ground-water recharge and discharge conditions.

The combustion of coal in-situ causes temperatures to increase to about 900°C. The heat generated by the chemical kinetics supplies energy to the gasification process and, in conjunction with extraction of gases, sets up a complicated chain of events which causes changes to the physical and chemical environment of the ground-water system. In the Soviet Union, measurements and observations made of commercial-scale underground coal gasification operations indicate that changes to ground-water flow do occur (Olness and Gregg 1977). The combination of high temperatures and product extraction causes a hydraulic sink in the flow system, which results in a decrease of hydraulic potentials and of the water table in and around gas generators. Water levels were observed to return to normal several months after gasification operations ceased. Whether such conditions will occur at the experimental coal gasification operation in Hoe Creek in northeastern Wyoming is not yet known.

Changes in the chemical composition of rocks have been observed at Hoe Creek (Mead and others 1979). The changes were caused by heat from hot product gases and by gas from the gasification zone that had penetrated surrounding rocks. Carbon and sulfur were removed, and dissociated iron oxides released oxygen. Slag, which is less permeable to gases than is the natural rock (despite the presence of large pores), was formed.

In coal gasification operations, removal of structural support to the overburden will cause roof collapse an s w l caving underground

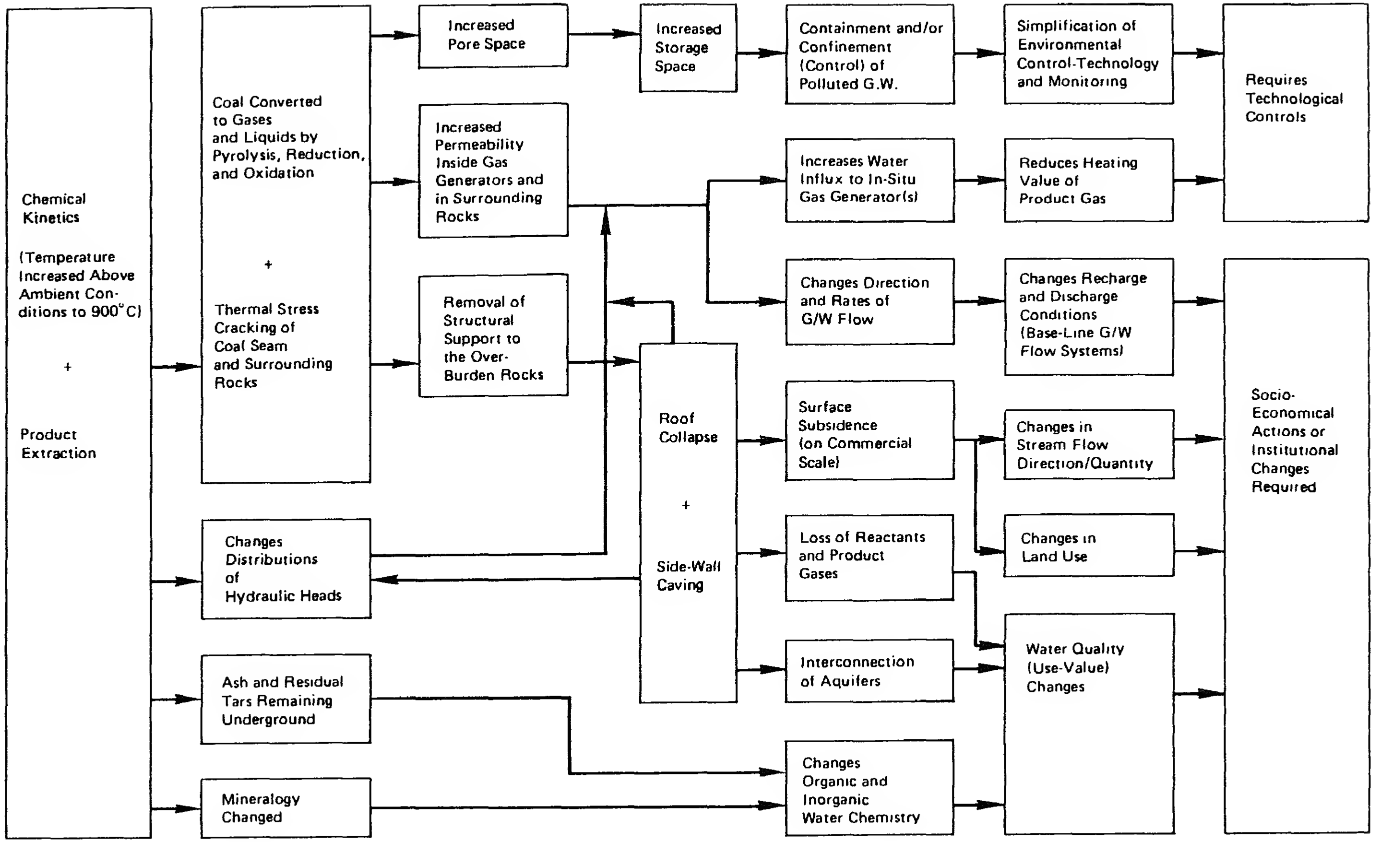


FIGURE 4.13 Flow Chart of Effects on Ground Water as a Result of Underground Coal Gasification

and may eventually lead to surface subsidence, loss of injected reactants and product gases, and interconnection of aquifers. The effect of surface subsidence, which depends on site-specific conditions and relative scale, may cause changes in stream flow and land use. Under commercial-scale operations, linked vertical well (LVW) technology applied to thick and nearly horizontal seams will have a greater effect on surface subsidence and changes in stream flow than the use of steeply dipping bed (SDB) technology. Subsidence has been observed at Hoe Creek; however, in the area of maximum subsidence, the ground had sunk less than 0.5 meter after several years. Farming at the gasification site was resumed upon removal of the gasification piping.

Ash and residual tar, mineralogical changes, loss of product gas, and interconnection effects will cause changes in water quality that may reduce the potential uses of ground-water and surface-water resources. Interconnection of aquifers will cause changes in water quality and head distributions in affected parts of ground-water flow systems. At the Hoe Creek site, a return of ground-water flow resulted in a leaching of the gasification cavities and an alteration of the chemistry of the ground water. Table 4.1 illustrates the observed changes in water chemistry resulting from in-situ mining of two coal seams at Hoe Creek.

Contaminants may be easily confined to the region of the gasification zone by increased storage capacity. The magnitude of the effect is minimized by controlling the movement of contaminants away from the gasifier. If operating pressures and natural hydraulic gradients are low and interconnection of aquifers is minimal, the contaminants tend to remain where they were generated; thus, control technologies and environmental monitoring can be greatly simplified for underground coal gasification.

Underground coal gasification in the eastern United States may not become commercial on a large scale because of the higher population densities and the diverse problems of land ownership and access rights that have removed land and water resources from consideration. Large and sudden changes in topography over small distances (e.g., Appalachian coal regions) will make the logistics of gas generator construction difficult. The large population densities will impose social and environmental constraints which will preclude widespread development. Many domestic needs for water are already fulfilled by water wells in eastern rural areas. Coal seams may also impose natural constraints because of their low content of volatile components, low natural permeability, and tendency to swell when heated (which will further reduce permeability necessary to conduct a burn of the coal seam). In some instances, small-scale underground coal gasification may be a viable source of energy for small rural communities (populations of up to 100 people) and for small industries such as brick works, bakeries, and certain manufacturing.

An opposite situation exists in most of the West where areas of land exist which could support commercial-scale underground coal g[illegible]fication and where population densities are much less than the

TABLE 4.1 Changes in water chemistry as a result of underground gasification at Hoe Creek, Wyoming

Parameter or Ion	Baseline	Range Aft In-Situ Min
temperature (°C)	15	≤ 120-600
pH	6.8-8.4	5.2-8.2
total dissolved solids	600	5000-12,
NH_4	7.6	1200-400
Na + K	20-80	11-500
Ca	50	300-500
Mg	10-100	60-200
Fe	1-2	8-900
Cl	20-100	30-250
HCO_3	200-400	200-400
SO_4	14	300-100
HS	85	35-860
S_2O_3	-	1500-250
$NO_2 + NO_3$	-	-
H_2SO_3	-	50

Dissolved gases in Water Samples

Nitrogen : 8.6% ; Oxygen : No measurable quantity.

Carbon Dioxide : 76.1% ; Hydrogen : No measurable quantity.

Carbon Monoxide : 0.47%; Gas saturation 85.6 mg/l.

Methane : 0.43%,

SOURCE: Modified from Mead and others 1979.

operators and some land owners, but there will be fewer landowners with which operators must bargain.

Because of higher population densities in the East, the market for production gases will be close to small gas generator systems. In the West, however, markets for product gases must be developed by expanding existing industries, by expanding gas transportation capabilities, or by bringing in new enterprises.

Overall, given the economical, social, and environmental constraints that may be imposed, underground coal gasification may supply only a small part of the nation's energy needs, and even then only in regions of both the East and West where the markets for product gases are close to the gas generators.

Alluvial Valley Floors

Another special problem is presented by alluvial valley floors in the West. Public Law 95-87 (discussed further in Chapter 7), contains provisions that severely limit coal mining on alluvial valley floors. River and stream valleys of the arid and semi-arid West are critically important to both the agricultural and ecological productivity of the region. Although occupying only a small proportion of the West's vast land area, the valleys produce far more biomass per acre than do the dryer upland sites because they offer accessibility to water and fertile alluvial soils. Ecologically, western river valleys are characterized by a diverse biota. Many plant and animal species occur only in valley settings. Even birds and large animals that spend much of their time in sparsely vegetated upland areas rely upon the valley ecosystems for food, water, and cover, both diurnally and seasonally. Without the valleys, the ecological productivity of much of the West would be far below current levels.

Agriculturally, the western livestock industry depends on valley lands, and the availability of valleys controls the size of livestock herds. During the warm seasons, livestock grazes throughout upland areas, most of which are public lands. The valley lands, many of which are privately owned, supply winter pasture, land that is cultivated to produce essential livestock feed, and sites for ranch residences and buildings. Feed grains, fruits, and vegetables are grown in some major river valleys, although the crops are less significant, both areally and economically, than livestock ranching to the agricultural economy of most of the inland West.

Coal mining, along with urbanization and road building, threatens to alter some western valleys and to displace both agriculture and the active biota, at least temporarily. The major impact of mining involves changes in the land surface and its vegetative cover, subjects beyond the scope of this report. However, coal mining also disturbs

Chapter 5.) Lowering of water tables and reductions in water quality are effects that produce impacts upon existing agricultural and ecological systems. The impacts may extend far beyond the surface area actually disturbed by mining and may persist well after mining ends and the surface is restored. (Chapter 7 discusses the use of appropriate reclamation techniques that may achieve a degree of post-mining site productivity superior to pre-mining conditions, for agricultural, if not for natural, ecosystems.)

From a strictly hydrogeological perspective, a clear definition of an alluvial valley floor is difficult. Hydrogeological considerations are not the only pertinent matters and may not be among the most important. Nonetheless, it is important to understand the relationship between hydrogeology and alluvial valley floors, and the activities that affect both.

The intensive agricultural use of alluvial valley bottoms causes ever-changing hydrological conditions, particularly those of recharge, water quality and consumptive water use. The bottom lands are cultivated, irrigated, and used for pasture. Crops with various water-consumption rates and rooting depths are grown; some of the lands are used interchangeably for cropping or pasturing. Water courses are sometimes deepened to provide better drainage and sometimes obstructed to inhibit drainage. All of these activities cause hydrological changes not commonly considered detrimental to agricultural productivity. Mining of coal could be expected to have the same kinds of hydrological effects as does agricultural use of alluvial valley floors. Mining operations are prohibited where significant areas of alluvial valley floors (as determined by regulatory agencies) might be disturbed. For further protection, mining near such areas is allowed only if regulators are convinced that no significant hydrologic effect will occur.

Federal regulations specifically require that mining not be allowed to interrupt, discontinue, or preclude a significant portion of any farm's agricultural production. However, temporary interruptions from mining can be more than offset by improving the land through innovative mining and reclamation procedures. Beneficial post-mine impacts might include expansions of irrigable acreages by optimizing water-table depths through land reclamation (raising water-logged surfaces and lowering and smoothing higher nonfarmable surfaces) and improvements to soil fertility and ground-water quality by replacing saline soils and overburden with more favorable materials. Such improvements would require improving and expanding current mining techniques and hydrogeological technology.

The alluvial valley floor provisions of PL 95-87 presume that agricultural lands are and will be more important to the nation's well-being than the coal deposits that underlie them. If that presumption proves incorrect, it could be more costly economically in the future to exploit the coal underlying those areas.

The special problem of coal mining in or adjacent to alluvial valley floors raises several issues. One is the difficulty of developing a te h y dequat definition of an al uval va ey

impacts of mining in those areas on agricultural productivity. A third is the difficulty of weighing the relative benefits and costs of mining against those of agriculture.

Abandoned Mined Lands

Disturbance of the environment from mining can continue after operations cease because the surface of the land has been altered. Before the surge of public environmental awareness of the past couple of decades, which resulted in new and revised state mine-reclamation laws and culminated in Public Law 95-87, many surface- and underground-mining operations left disturbed lands and polluted waters in their wake. In addition to esthetic considerations, mining affected the safety and health of the local residents and had adverse impacts on the economic and social well-being of the areas.

However, such abandoned lands have not been conclusively defined. The U.S. Soil Conservation Service has defined "disturbed lands" as those needing reclamation, but for which reclamation is not required by law. The U.S. Bureau of Mines defines "abandoned lands" as those not reclaimed according to federal or state laws or not restored to a useful condition (Office of Surface Mining 1980). The Federal Surface Mining Control and Reclamation Act and the Office of Surface Mining regulations state that offsite problems enlarge the significance of abandoned lands and that neither current nor prior owners have legal responsibility to reclaim that land.

Attempts to quantify the problem of abandoned, mined land on a national scale began about 15 years ago, when the U.S. Department of the Interior conducted a survey to determine the nature and extent of the lands affected by surface mining (USDI 1967). In 1974, the Interior Department's Bureau of Mines attempted to refine and update that information for all mining, and, in 1979, the Agriculture Department's Soil Conservation Service attempted to do the same for surface mining of all minerals (Paone and others 1974, U.S. Soil Conservation Service 1979). Recent estimates by the U.S. Bureau of Mines indicate that an additional 0.4 million acres of land were used by the coal industry during the period 1972-1977, but abandoned, mined land has not significantly increased during that period because of existing federal, state, and local reclamation laws. However, the Bureau also estimates that approximately 0.4 million acres of lands that were surface mined for coal from 1930 to 1971 remained unreclaimed in 1974, and thus abandoned (Johnson and Miller 1979). Land overlying underground coal mines has been estimated to total 7.1 million acres, of which 1.9 million acres have already been affected by subsidence of the land surface. Some of the remaining 5.2 million acres will also subside; of this amount, 0.4 million acres conceal this hazard in urban areas (Johnson and Miller 1979).

Waste banks are another result of mining that poses reclamation problems. Such banks (also called culm banks or boney piles) are piles of material rejected in the processing of coal and related rock during underground mining. The material, which contains combustible coal

gob). Waste banks cover an estimated 0.2 million acres. Nearly 300 banks covering more than 3,000 acres are on fire; the fires occur in half of the 26 coal-producing states (Johnson and Miller, 1979). In addition, mine fires present in both abandoned underground mines and in the underground extensions of abandoned surface mines and natural outcrops of coal create a special reclamation problem and a potential hydrogeologic problem.

Acid drainage from abandoned mines received considerable national attention as a result of the 1967 report by the U.S. Department of Interior and a 1969 report by the Appalachian Region Commission. The problem of acidic drainages resulting from coal mine operations is greatest in the Appalachian coal regions, and the Commission's report noted that 5,700 miles of stream were affected. Almost 80 percent of the acid mine drainage came from abandoned or inactive coal mines, and more than 70 percent originated in underground coal mines (Johnson and Miller 1979). In addition to acid, stream pollutants that result from mining include sediment, sulfate, iron, and hardness; the Commission's report stated that 10,500 miles of streams and rivers were affected by all five of the pollutants. Table 4.2 shows the extent and magnitude of the various problems related to abandoned coal-mined lands.

The effects of abandoned lands upon the hydrogeologic system are similar to those of various coal mine operations. Spoil and waste materials of surface-mined lands provide the environment necessary for production of mine leachate and for subsequent changes in ground-water quality. Some surface-mined lands also have an improved infiltration capacity which increases ground-water recharge, thereby altering local ground-water flow systems. Underground mine workings can yield poor water quality and in some cases introduce acid mine drainage to surface water. Mine shafts and air tunnels that intercept ground-water flow and areas of mine subsidence will also alter ground-water recharge and other ground-water flow relationships.

Reclamation of abandoned lands with the goal of improving the hydrogeologic systems should be carefully assessed. Merely reclaiming the land surface of abandoned mine sites may not change present ground-water conditions or may cause further ground-water degradation. Reclaiming areas in which ground-water quality can be improved by reclamation should be weighed against any future costs and benefits of not reclaiming the site. Thus, reclamation of abandoned lands needs to be evaluated on a site-specific basis, taking into account the existing hydrogeologic system of the abandoned mine area and the probable ground-water system that will result from the reclamation effort. Indiscriminate reclamation of abandoned mined lands may leave many hydrogeologic systems without improvement.

Waste Disposal in Mined Lands

At many surface mines, wastes have been placed in mine pits before or during backfilling operations. At some surface mines, municipal garbage or industrial wastes are disposed of in the pits as an

TABLE 4.2

Effects Related to Abandoned Coal-Mined Lands

State	Acres of Abandoned Lands (1,000x)	Acreage of Potential Subsidence (1,000x)	Acres of Waste Banks (1,000x)	Fires in Waste Banks (1,000x)	Fires in Mines & Out-crops (Number)	Degraded Mine Drain-age (miles)	Acid Drain-age (miles)
Alabama	6.8	11.7	9.1	0.1	0	50	30
Alaska	1.0	0	0	0	3		
Arizona	0.8	0	0	0	10		
Arkansas	0.8	1.3	0.4	0	0		
Colorado	1.7	6.3	2.0	0.13	47		
Illinois	60.5	41.8	16.0	0.14	0		
Indiana	32.7	10.9	11.9	0	0		
Iowa	2.2	3.8	0.7	0	0		
Kansas	5.4	2.9	0.4	0	0		
Kentucky	51.5	37.2	22.9	0.16	5	1,140	50
Maryland	1.2	2.9	0.4	0.003	2	200	200
Michigan	0	0.4	0	0	0		
Missouri	9.2	2.5	0.5	0	0		
Montana	1.7	1.7	0.5	0.006	65		
New Mexico	2.2	1.7	0.4	0	9		
N. Dakota	7.5	0.4	0.4	0	15		
Ohio	55.8	21.8	7.3	0.02	7	1,750	560
Oklahoma	3.8	1.7	0.4	0.001	0		
PA	87.6	151.4	33.5	1.3	42	3,900	3,430
S. Dakota	0	0	0	0	2		
Tennessee	4.3	5.0	2.1	0	0	280	60
Texas	0	0.8	0	0	1		
Utah	0.2	3.8	2.1	0.03	17		
Virginia	7.2	13.4	8.6	0.08	0	70	20
Washington	0.3	1.7	0.3	0.1	2		
West Virginia	37.5	89.1	52.9	1.2	8	3,130	1,390
Wyoming	2.3	4.2	1.6	0	26		
Total	383.2	418.4	174.1	3.22	261	10,520	5,740

Wastes from coal-cleaning plants also are buried in surface mine
are sometimes covered with clayey material of low permeability.
some surface mines in the West, fly ash and scrubber sludge are
in the pits.

Potentially toxic materials such as coal-cleaning wastes, fl
and scrubber sludge are buried in mined land with the expectatio
they will be permanently isolated from the hydrologic regime and
biosphere. Whether this method of waste disposal is effective
economically and environmentally depends on how permanently thos
materials are isolated.

Another kind of waste involves the large volumes of oil used
lubricate heavy moving equipment. Service crews commonly drain
spent machine oil on the active mine surface in the pits. The w
oils, as well as fuel from machine leakage and spills, become
incorporated in the backfilled mine and can pose a hazard to
ground-water quality because of the organic contaminants in the
and because of the ability of oily substances to mobilize natura
toxic constituents such as heavy metals.

At the present time, little is known about the effects on gr
water of wastes disposed of in surface mines. Pits at some mine
or some pits at a particular mine may be situated in hydrogeolog
settings suited to waste disposal. However, wastes buried at
unsuitable sites may, for a period of time, cause no noticeable
degradation of ground-water quality. But eventually, as leachin
the waste by infiltrating water occurs and as the leached contam
migrate in the ground-water flow system, the impact of the burie
wastes may be manifested in contaminated wells or springs or in
of contaminated ground water into surface-water bodies. Many d
or hundreds of years could pass before such an effect would be o

It is assumed that mined land has potential for long-term is
of wastes from the biosphere at some sites and not at others, th
critical problem becomes identifying suitable sites. If burial
wastes in mined land is a major reason for selecting a particula
the screening of the mine site should be designed so that specif
aspects of the hydrological investigation focus on this reason.

In the West, the question of waste disposal in mined land ha
important implications because power plants located at mining si
becoming increasingly common there. Large volumes of waste in t
of fly ash and scrubber waste are produced in the power plants.
open pits are an obvious place to dispose of the wastes during t
normal sequence of mining, backfilling, and land reclamation.

When fly ash of the type most commonly produced at coal-fire
plants in the West is in contact with water, the pH of the water
to the range of 10 to 12.5, far above the natural pH range of 6
In North Dakota, recent laboratory experiments and samplings of
water in reclaimed land where fly ash has been disposed have sho
the high pH water contains dissolved arsenic, selenium, and moly
at concentrations much above the limits for drinking water speci
regulations. Such water is, therefore, toxic if consumed by hum
v ve o . n erms of its ability to cause high concentrati

eastern coals causes a disposal problem similar to that for many hazardous industrial wastes.

The influence on ground water of flue-gas scrubber sludge from the same power plants is different from the high pH and high arsenic and selenium ground water produced from fly ash. When the sludge is in contact with water, the pH of the water is generally between 7 and 9 and none of the toxic metals and nonmetals occurs at high concentrations. The water, which acquires high concentrations of sulfate and major cations (such as calcium, magnesium, and sodium), is not potable for the same chemical reason (high sulfate content) that much of the natural ground water in the West is not potable. Although the stated purpose of scrubber systems is to diminish the adverse effects of coal-fired power plants on the atmosphere and the land surface, a major indirect benefit of scrubber systems may be the much less severe effect of sludge disposal on ground water in mined land compared to that of fly ash. Although fly ash causes high arsenic and selenium levels in ground water, disposal of it in reclaimed land may be necessary because in some hydrogeologic settings, other, less hazardous options may not be feasible because of the large volume of the waste.

At present, research on the effects of fly ash and scrubber sludge on ground water, with emphasis on the assessment of long-term impacts on water resources, is in its infancy. Hydrogeologic studies of surface mine sites at which power plants are or will be located have generally focused on the effects of mining and land reclamation without detailed consideration of the special nature of the problem when the reclaimed land contains fly ash or sludge.

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CHAPTER 5

SPECIFIC EFFECTS AND IMPACTS OF COAL MINING ON GROUND-WATER RESOURCES

INTRODUCTION

In this chapter, examples are presented from both eastern and western coal provinces of observed effects on the hydrogeologic systems associated with coal mining. Also discussed are some of the social and economic impacts that result from mining-induced changes in a hydrogeologic system. Where the number of mines and types of effects are too numerous to detail, observed effects of mining are presented as referenced studies and are related to the representative settings discussed in Chapter 4.

Despite the usual emphasis on negative aspects, coal mining can produce a number of beneficial hydrogeologic effects. For example, mine spoil material is very permeable and the infiltration rate remains high once the mine spoil is reclaimed. Area surface mining produces large areas covered with low-relief mine spoil which forms large ground-water reservoirs. The permeable nature of the spoil allows a high rate of ground-water recharge. In turn this decreases surface runoff, erosion, and flood potentials. Ground water stored in the mine spoil is released slowly to springs, seeps, and water courses and provides a higher sustained baseflow to streams.

Lakes forming in surface mines commonly have a pH greater than 7 and are frequently used for recreation, including fishing, boating, and swimming. For example, in east-central Ohio, an area that had been strip mined has been reclaimed and turned into a major park and recreation area.

Additional benefits from coal mining occur where abandoned underground mines or abandoned parts of working mines supply public water, as in some areas of Appalachia. Flooded underground mines are also a potential source of water supply for low-flow augmentation and

Eastern Province

In the Eastern Province, the observed effects of coal mining are discussed for the Appalachian Regions, the Pennsylvania Anthracite Region, and the Narragansett Coal Region.

Northern Appalachian Coal Region

The effects of surface and underground coal mining in the Northern Appalachian Coal Region have been portrayed in the discussions of Representative Settings A, C, and D (Figures 4.5a, c, and d) in Chapte 4. Prior to enactment of state and federal reclamation and water-quality laws, acid mine drainage was the largest single effect o coal mining within the region. Not only had actual mining sites been affected, but downstream alluvial and bedrock aquifers had become contaminated. Since enactment of the laws, the quality of water from newly reclaimed surface and underground mines has improved, and downstream contamination of alluvial and bedrock aquifers has decrease

Dewatering of near-surface aquifers overlying underground mines ca be significant. As the depth of aquifers increases, the likelihood of adverse effects on water wells decreases. Where mining has resulted i wells being dewatered, water often returns to the wells in a greater quantity after a period of 1 to 6 months, although the water is often of poorer quality.

The abandonment of some underground mines and the reestablishment of the ground-water regime has sometimes improved water quality to the extent that ground water can be withdrawn from the mine for municipal water supplies. Owing to the low permeabilities of many of the rocks in the region, surface mining has increased infiltration and decreased runoff, resulting in an increased quantity of ground water in storage for future use.

Central Appalachian Region

Approximately 95 percent of the Central Appalachian Coal Region ha conditions similar to those depicted in Representative Setting A (Figure 4.5a). The Upper Cumberland district and the Pine Mountain thrust sheet in eastern Kentucky and the Caryville, Pine Mountain, an Cumberland Mountain fault zones in the southern plateau region of eastern Tennessee display the characteristics of Representative Settir D (Figure 4.5d); the areas comprise about 5 percent of the entire region. Underground mining accounts for 83 percent of the coal production in the region in 1975.

Of the ground water and mining conditions observed in the Central Appalachian Region, erosion and siltation are the major concerns. Aci water does not appear to be a problem. Acid water could be produced among the lower coals, but most mining is conducted in non-acid-beari overburden.

Air shafts and underground mines can serve as large ground water drains. A study in West Virginia indicated that wells become dry when less than 250 ft. of overburden exists between the bottom of a well and an underground mine. Air shafts constructed without pregrouting drain large quantities of ground water, and studies have found that in many cases, wells less than 75 ft. deep within a mile of such a shaft have dried up within a few months (Ahnell and Rauch 1978).

Southern Appalachian Region

The geologic configuration of the coal-bearing seams in the Plateau and Warrior coal fields differs markedly from those of the Cahaba and Coosa fields of the Southern Appalachian Region. The difference radically affects the nature of the short- and long-term effects of coal mining.

In the Plateau and Warrior coal fields, the relatively low-dipping beds display the characteristics of Representative Setting A (Figure 4.5a). In this setting, the mine may have both an immediate and a long-term effect on the hydrologic regime. However, investigations that measured water-quality responses to mining showed that, although total dissolved solids increased, acid mine drainage was not a widespread problem. Two studies found that water quality of a stream flowing past an active mine had increased alkalinity, pH, suspended solids, specific conductance, iron, magnesium, and chlorine (Puente and Newton 1979, Shotts and others 1978). In general, increases in mineralization of drainages were found to be of the calcium-magnesium, bicarbonate-sulfate type. The high sulfate concentrations suggest that some pyrite oxidation is taking place. However, the small amount of acidity produced is being neutralized by the alkalinity generated by the adjoining carbonate strata and the thin and discontinuous limestone members within the Pottsville formation. Most of the aluminum, iron, magnesium, potassium, and sodium, and all of the chromium, copper, lead, and nickel were found to be associated with suspended matter and not as dissolved ions (Shotts and others 1978). Since the pH of the mine drainages tends to be high, the solubility of the metals (with the exception of aluminum) is low, and ionic mobility would be suppressed.

An aquifer system that is interbedded with impermeable beds tends to restrict the deep, downward migration of a potential pollutant. The alkalinity generated by the limestone lenses maintains a high pH, which effectively immobilizes the few soluble heavy metals. The clays and the attached metals tend to be filtered out in aquitards, thereby preventing heavy metal transfer to the ground-water regime.

In general, the combination of an alkaline ground-water regime and the physical retention capacity of the clays ensures, to some extent, the protection of the ground-water resources from heavy metal contamination. Acid water does not appear to be a common problem in these areas; acid concentrations produced are low and easily neutralized by the available alkalinity. However, in the short term, mining in the areas can affect water quality by increasing total

prevail and affect the mineral content of the water. As long a
acidity from sulfates is produced, the potential exists for inc
mineralization of water. However, in the long term, the inunda
a mine by alkaline waters will suppress pyrite oxidation, restr
production, and eventually reduce the total dissolved solids co
the water.

In the Cahaba and Coosa coal fields, the steeply dipping coal-bearing strata play an important role in the effect of a c on the ground-water regime. For those fields, Representative S C and D (Figures 4.5c and d) are appropriate. As in the Warrio Plateau fields, the presence of carbonate material, either with stratigraphic sequence or tectonically juxtaposed by thrust fau generates alkalinity in sufficient concentrations to offset and neutralize the minor amounts of acid produced. Most waters in areas are of the calcium, magnesium, bicarbonate type, and in g most water-quality problems are similar to those discussed abov

A short-term effect of the mining operations on the water r in the coal fields results from mine drainages that are pumped surface-water supplies. Because many of the mines are located steeply dipping strata, they must be dewatered during the activ phase. In turn, surface waters are affected by the mine drain the ground-water system in the area of a mine is partially dewa Although the effects on surface-water quality are the same as d above, the total impact is less deleterious owing to the limite amounts of mine drainage discharged to the surface-flow system

In these areas, the long-term effect of mining on water re should decrease with time. Here, the down-dip mining in the sy basins will cause less of a pollution problem than that caused nearly horizontal mines common to the other fields, because th opening in a horizontal mine will flood after mine operations c Under these conditions, the potentially toxic acidic material inundated; the oxidation of the pyrite is retarded; and, thus, mineralization of the water is decreased. When the dewatering ends, the ground-water regime becomes re-established and the s dewatering effect of the mine is mitigated. Thus, in the Caha Coosa coal fields, where beds are generally steeply dipping, t long-term effect of coal mining on the ground-water regime is pronounced as in the Warrior and Plateau fields.

Pennsylvania Anthracite Region

Conditions in the Pennsylvanian Anthracite Region are simi those depicted in Representative Settings C and D (Figures 4.5 d). Both surface and underground mining techniques are used t coal in this region of steeply dipping bedrock. The infiltrat water into the underground mines has always been a serious pro 1970, more than 80 tons of water had been pumped from mines in region for every ton of coal produced (Berger and Associates 1 Many of the mines are interconnected and, when one mine ceases

Many abandoned mines contain pools of water, the location and size of which are often unknown; much of this water is acidic. When modern underground mines penetrate the pools, the inrush of water can kill or injure miners. In addition, many active or abandoned surface mines are scarred by numerous open holes containing acidic water. Eroded spoil piles and barren waste banks also dot the region.

Narragansett Coal Region

Development of the coal resources of the Narragansett Coal Region of Rhode Island and Massachusetts could have a wide range of effects on water and other resources, although some of the environmental effects could be mitigated or avoided (Frimpter and Maevsky 1979). Analyses indicate that sustained high rates of seepage to mines are not anticipated unless the mines are close to large surface-water bodies, or to water-saturated sand and gravel deposits. Mining is expected to interfere with nearby domestic wells that tap bedrock, as mining operations could dewater the bedrock aquifer locally and thus rapidly affect water levels in domestic wells as far as hundreds of feet away (Frimpter and Maevsky 1979). Neither acid mine drainage nor iron pollution of water supplies is predicted, because mining in the region is not expected to expose large quantities of fine-grained pyrite to the air and thereby limit oxidation.

Interior Province

Knowledge of the effects of mining on the ground-water regime in the Interior Province comes from field observations and research efforts in the Eastern Interior and Western Interior Regions. Mining operations in the Michigan Basin (Northern) and Texas Bituminous (Southwestern) Regions are small, and therefore are not discussed in this chapter.

Eastern Interior Coal Region

Surface and underground mining operations in the Eastern Interior Coal Region have been confined mainly to a narrow belt that coincides with the outcrop of coal-bearing strata. Representative Setting B (Figure 4.5b) characterizes the conditions in the region. With few exceptions, coal and rock units are essentially flat-lying and capped by thick deposits of glacial drift. In the southeastern portion of the region, called the Shawnee Hills, bedrock "islands" are surrounded by glacial outwash. Shawnee Hills probably comprises less than 5 percent of the entire area and is not considered a major topographic/hydrogeologic setting.

In the Eastern Interior Coal Region, there are two major sources of poor quality recharge to ground-water systems resulting from coal mining operations: (1) surface mine spoil, and (2) coal-processing wastes, primarily slurry and gob. Mine spoils in Fulton County,

effects on water quality; increases in the concentration of s
potassium, calcium, iron, magnesium, lead, manganese, nickel,
cadmium, zinc, nitrogen, chloride, sulfate, and alkalinity we
observed when ground water from mine spoil wells and wells ir
unmined areas were compared (Pietz and others 1974).

Water-quality degradation related to waste disposal resul
downward movement of precipitation infiltrating gob piles. A
pile, most of the accumulated water in the recharge mound wil
dissipate by seepage around the edges of the pile at its cont
the low-permeability sediments. Some leakage to the water ta
occur, primarily at slurry lagoon sites but also at gob piles
the disposal facilities are located on permeable sediments, s
glacial or alluvial sands and gravels, the degradation of loc
ground-water quality by leachates will be limited. Deteriora
shallow ground-water quality in the vicinity of a gob pile lo
Macoupin County, Illinois, was observed by Schubert and other
In water from one well in that area, the concentrations of su
acidity were 5,739 mg/l and 8,370 mg/l, respectively. Metal
concentrations exceeded recommended drinking water limits by
orders of magnitude. However, the concentration of contamina
decreased significantly about 400 ft. from the refuse pile.
be noted, however, that ground-water too mineralized for most
occurs naturally at depths of 100 to 300 ft. throughout the E
Interior Coal Region. The occurrence of poor-quality ground
shallow depths limits the potential impact of mining operatio
ground-water resources outside of the major river valleys.

Underground mining has a limited potential to dewater aq
lower potentiometric surfaces in the region. In the Illinois
most Pennsylvanian-age rocks have a low hydraulic conductivi
result, hydraulic gradients toward underground mine openings
over a short distance. At an abandoned mine located east of
Missouri, Cartwright and Hunt (1981) observed that the shallo
ground-water flow system was not affected by collapsed mine
ft. below the surface. This is probably due to the soft, pla
nature of many of the Pennsylvanian shales; fracture propaga
limited or prevented because of the "self-sealing" nature of
shale. Situations where underground mining could induce low
the potentiometric surface in bedrock or unconsolidated aqui
the result of the interception of, or proximity to, channel
sheet sands, or bedrock valleys filled with Pleistocene or r
and gravels. Most mines are not located in channel sandston
buried valleys because (1) these areas usually contain no co
water inflow is difficult to handle, softens mine floors, an
the complexity and cost of the pumping system.

With little or no potential for widespread changes in th
potentiometric surface and the low topographic relief charac
the Eastern Interior Coal Region, major changes in the locat
ground-water divides and in the direction of ground-water fl
unlikely. Because even the most permeable bedrock units hav
hydraulic conductivity, overburden broken by blasting, remov

percent void space. The increase in porosity greatly increases the amount of ground water in storage. In other words, the spoil acts as a large ground-water reservoir: it becomes a massive aquifer storing large volumes of water and is directly recharged by precipitation (Corbett 1968).

If a rubble zone (an accumulation of large blocks of rock that roll down the spoil slope) forms at the base of the spoil or if the spoil is not predominantly shale, a large increase in hydraulic conductivity occurs. In Muhlenberg County, Kentucky, data from a pump test of a well tapping the most prolific aquifer in the area, the Anvil Rock sandstone (member of the Lisman formation), indicate that the aquifer has a natural transmissivity of 24 gpd/ft. Analysis of pumping test data from a well completed in spoil left after mining the Lisman formation (which contained the Anvil Rock sandstone) gave a spoil aquifer transmissivity of 1,494 gpd/ft. and a hydraulic conductivity of 48 gpd/ft.^{2} (Herring 1977). The spoil aquifer well had a yield of 15 gpm, which is probably greater than most well yields in the county. With a drawdown of 12.64 ft., the specific capacity of the well is 1.19 gpm/ft.

Changes in stream flow and recharge potential are the major alterations in the water balance attributable to coal mining in the region. Reductions in flood flows and crest were caused by the creation of spoil aquifers following surface-mining operations in Indiana (Corbett 1968). From February 6 to 22, 1965, the flood flow from a mined drainage basin was 2.82 cu. ft. per second/square mile (cfs/mi^2), and the crest rate was 30.70 cfs/mi. Those amounts are 4.66 cfs/mi^2 flood flow and 61.68 cfs/mi^2 crest rate observed in an unmined basin.

Stream baseflow in mined drainage basins is much greater than that in unmined basins. If baseflow is increased, the amount of ground water in storage must also have increased. When this happens, stream flow is sustained or increased during periods of low rainfall when other streams in unmined basins have dried up. An adverse effect of the increased stream baseflow is the degradation of stream-water quality as mineralized ground water from spoil discharges to surface water. Grubb and Ryder (1972) observed that the total dissolved solids concentration in surface water from mined subbasins of the Tradewater River in Kentucky was 17 times that of water from unmined basins.

Western Interior Coal Region

Many of the representative settings shown on Figure 4.5 are possible within the Western Interior Coal Region. Both surface and underground mining can be used, but at present, surface techniques are more commonly applied. Owing to the general abundance of precipitation throughout the region, the water table is found at relatively shallow depths, often above the coal seams.

characteristics similar to those displayed in Representative
(Figure 4.5b). Relatively flat bedrock is covered by a mantl
glacial and alluvial material. In most cases, the water tabl
in these materials above bedrock. Mining in the setting will
dewatering of glacial, alluvial, and bedrock materials that l
the coal in the mine and in adjacent areas. Following mining
presence of backfilled materials may actually increase local
and, thus, available ground-water resources.

The geologic materials associated with the coal often con
pyrite, which may oxidize and lead to the formation of acidic
water following mining. However, the materials often contain
mineralized water prior to mining and consequently are rarely
major source of ground water. The low hydraulic conductivity
shallow bedrock limits the vertical movement of water and nor
protect deeper freshwater aquifers when they are present.

Bedrock conditions in the southern unglaciated portion of
region are similar to those farther to the north, except that
glacial cover is present. Bedrock is relatively flat-lying,
characteristics of this region are similar to those shown in
Representative Setting A (Figure 4.5a). The water table norm
in bedrock above the coal or in alluvium where it is present
river valleys. In the past, both surface and underground min
been used, but currently coal is mined by surface methods onl
effects of mining are similar to those described for the nort
glaciated portion of the region and include the dewatering of
overburden materials and the possible formation of acidic wat
Normally, only a few small domestic supplies will be affected
in the southern portion of the region.

In the Arkoma basin-Arkansas River valley, the bedrock is
into anticlinal and synclinal mountains. These dipping rocks
similar to those shown in Representative Setting D (Figure 4.
surface and underground mining methods are used and, in a few
affect small domestic water supplies by dewatering the overbu
materials. In general, however, Pennsylvanian rocks above th
are not widely used as regional aquifers because of their low
productivity and poor water quality. Most major municipal wa
supplies will not be directly affected by mining because thei
is the alluvium along the Arkansas River.

In areas mined by underground methods, roof collapse and
of the overburden increases hydraulic conductivity and enhanc
dewatering of overlying strata. Seals are needed after minin
the gravity drainage of potentially acidic water. The pyrite
of the coals in the area is lower than that in regions to the
(normally less than 3 percent); therefore, the formation of a
ground water should not be so great a problem.

Gulf Coast Province

Conditions in the Gulf Coast lignite region are similar to those depicted in Representative Setting E (Figure 4.5e). The unconsolidated to semiconsolidated deposits are normally flat-lying. Owing to existing physical and environmental conditions, surface mining of lignite in the region will have only limited and short-term effects on the hydrologic balance and ground-water quality at most mine sites. However, in areas where overburden is predominantly sand and where rainfall exceeds evaporation, the risk of ground-water contamination is greater. Because most commercial lignite deposits occur in fine-grained geologic sequences, the movement of ground water through most reclaimed mine spoils will be minimal. The migration of ground water with elevated total dissolved solid concentrations will also be limited.

Development of Gulf Coast lignite deposits is at an early stage, and thus few well-documented accounts of ground-water effects are available.

WESTERN UNITED STATES

Northern Great Plains Province

Observed effects of mining in the Northern Great Plains Province have centered around surface-mining operations in Montana, Wyoming, and North Dakota. In general, mining operations are conducted in relatively flat areas and are similar to those depicted in Representative Settings A, B, and C (Figures 4.5a, b, and c).

Southeastern Montana

Absaloka Mine. The Absaloka mine (formerly Sarpy Creek mine) was opened in 1974 and has since disturbed approximately 300 acres of land. Two coal seams, the Rosebud-McKay and the Robinson, are currently being mined. The coal seams are not very productive aquifers, but the quality of the small amount of water in the coal and overburden makes it the most desirable ground water in the area. The concentration of dissolved solids in the coal-seam water ranges from 100 to 3,000 mg/l; water in some other local aquifers contains as much as 5,000 mg/l dissolved solids (Montana Bur. Mines and Geol., and USGS 1978).

Because of the low productivities of the disturbed aquifers, inflow to the mine has been small enough that it has not been necessary to pump water from the mine. Water levels in observation wells around the mine have not declined, and the hydrologic effects of active mining to date seem to be negligible.

Little water has thus far entered the mine spoils. Two wells in

water. Water sampled from the other observation well con
mg/l dissolved solids, most of which were magnesium, calc
sulfate.

Rosebud Mine. The Rosebud mine has been operated sin
except for the 10 years between 1958 and 1968. The total
disturbed is about 10,000 acres. The coal seam provides
adequate water supplies to livestock and domestic wells a
heavily used where it lies within about 200 ft. of the la
Those areas nearly coincide with areas where the coal bed
economically mineable.

The quality of water in the Rosebud coal bed and in o
aquifers varies. Dissolved-solids concentrations range f
6,000 mg/l; the median concentration from 73 analyses in
was 1,700 mg/l. The waters contain various proportions o
magnesium, and calcium, and most contain high concentrati

The volume of inflow to Rosebud mine pits has only oc
been large enough to warrant pumping. As pits in the min
backfilled, a saturated zone as thick as 20 ft. has devel
mine spoils. Most of the water in the zone has entered l
unmined aquifers; some has entered the spoils vertically
and snow melt, especially beneath areas of poor surface d
Water levels in observation wells spaced outward from the
have declined perceptibly.

Tests of wells in spoils and in nearby undisturbed aq
Voast and Hedges 1977) provide evidence that the Rosebud
transmit water at least as efficiently as the natural aqu
Water in the spoils contains somewhat higher concentratio
dissolved solids than were found in water from the undist
aquifers. The natural diversity of water quality in the
comparisons difficult. A notable condition is the tender
quality in and near the mined area to change continually.
samplings at some of the wells during the past 4 years ir
water quality in the mined area varies; therefore, a tren
either increasing or decreasing salinity has not been inc

Big Sky Mine. The Big Sky mine was opened in 1969 ar
disturbed approximately 800 acres of land. The Rosebud a
seams are currently mined; they are also aquifers of loca
significance. The mine is located 2.5 miles southwest of
mine; therefore, geologic and hydrologic conditions arour
mines are similar. Active pits at the Big Sky mine recei
ground-water inflow than does the Rosebud mine, partly be
coal seams are being mined. Effluents pumped from the pi
mixtures of local ground waters; they have not caused deg
water quality.

Water levels in wells around the mine have declined s
began, but not to a great extent. Within one-quarter mil
active pit, declines of about 6 ft. have been measured; b
miles west of the mine, declines have been less than 1 ft
and Hedges 1977).

Results from test wells that penetrate mine spoils indicate that the spoils are much more capable of transmitting ground water than are the undisturbed coal-seam aquifers. Chemical analyses of the water in the spoils have found some relatively saline samples compared to those from the surrounding undisturbed area; some mined-area samples contained more than 7,000 mg/l dissolved solids. Most of the high concentrations are associated with spoils from the McKay coal seam overburden. Spoils-water quality in the Big Sky mine area has not varied greatly since sampling began, and there is no apparent trend toward increasing or decreasing salinity (Van Voast and others 1978).

West Decker Mine. The West Decker mine was opened early in 1972 and has since disturbed about 1,000 acres of land. The Dietz-1 coal seam, which is being mined, is an important aquifer westward from the mine. The West Decker mine is different from others in Montana in terms of geologic and hydrologic conditions. Overburden at the mine contains much more sodium than does overburden at other mine sites. Consequently, the ground water also contains relatively high concentrations of sodium. Sulfate, a major constituent in waters of other mines, is nearly absent in water from the Dietz-1 coal seam. Instead, bicarbonate is abundant, in some places to the degree of oversaturation. When oversaturated with bicarbonate, the water is somewhat like artificially carbonated soda water. Dissolved-solids concentrations in water of the Dietz-1 coal seam are uniformly between 1,000 mg/l and 2,000 mg/l (Van Voast and Hedges 1975), in contrast to the more diverse and generally higher values for waters in other coal mine areas.

Another different hydrologic condition in the area is the presence of the Tongue River Reservoir near the eastern end of the mine. The reservoir is a hydrologic boundary that limits any eastward effects of mining on the ground-water system.

Water levels in wells around the West Decker mine have declined much more than those near other Montana coal mines. Within 2 miles west of the active pit, declines have been more than 10 ft; close to the pit, water levels have declined as much as 40 ft. Ground-water inflow to the mine pit has been sufficient to necessitate pumping and subsequent discharge to the Tongue River. Discharge to the river is an acceleration of naturally occurring ground-water discharge. In spite of the declining water levels, wells within a mile from the mine still provide adequate supplies of ground water for residences, a tavern, and a restaurant. Mining operations, however, are moving progressively closer to the wells, which will eventually have to be deepened to other aquifers.

As successive westward mine pits are opened and the depleted ones backfilled with spoils, ground water readily reenters the mined area. At research wells in mine spoils, water levels have risen as much as 30 ft. since measurements were begun in May 1975. Tests of the research wells have given results similar to those found in other mined areas: the spoils are at least as capable of transmitting water as were the coal-seam aquifers that have been removed.

Water in the spoils is chemically different from that
Dietz 1 coal. Dissolved-solids concentrations of some sa
exceeded 6,000 mg/l, and the major constituents are sodiu
(Van Voast and others 1978). Despite the strikingly high
effects of eventual flow of the waters to the Tongue Rive
will probably be negligible because of dilution by the re

Wyoming

Many mines are operating in Wyoming, but data on hydr
characteristics are available for only two mine sites. S
hydrologic character of spoils and the quality of water i
are being conducted by the Argonne National Laboratory (D
Olsen 1977, Schubert and others 1978) at the Big Horn mi
Sheridan in northern Wyoming, and by the Wyoming Water Re
Research Institute (Davis and Rechard 1977) at the Belle
Gillette. Reconnaissance-level data on water quality of
mines have been described by Hounslow and others (1978).

Big Horn Mine. The Big Horn mine is located about 10
southwest of the West Decker mine in Montana. The geolog
hydrologic conditions of both mines are similar, includin
River nearby. The Big Horn mine has been operating for m
years and has thus far disturbed about 1,500 acres of lan
seams are mined, and two pits are active. Dettman and Ol
report that one of the pits penetrates some of the alluvi
river, and the inflow must be pumped for mining to contin
water-level data for surrounding wells are reported, so t
the inflow on area water supply are unknown. Concentrat
dissolved solids in some of the dewatering effluent to th
are almost seven times greater than concentrations of the
but no effects on river quality have been detected becaus
flow in the river is 50 to several hundred times that of
rate. Quality of water (Schubert 1978) in spoils at the
is similar to that at the Decker mine; specific-conducta
range between 6,000 and 9,000 micro-ohms per centimeter.

Belle Ayr Mine. The Belle Ayr mine has been in oper
1971 and has thus far disturbed about 1,000 acres. The c
removed is about 70 feet thick and allows small volumes
the mine. Preliminary data and interpretations by Davis
(1977) indicate that changes in ground-water levels caus
dewatering are not detectable more than one-quarter mile
Analyses of water in spoils at the Belle Ayr mine have t

Rosebud and Kemmerer Mines. At the Rosebud and Kemmerer mines in southeastern and southwestern Wyoming, respectively, some water from mine pits has been found to be much more highly mineralized than the nearby ground and surface water (Hounslow and others 1978). In both cases, the enrichment of calcium, magnesium, and sulfate were judged responsible for the increased concentrations of total dissolved solids. In neither case was any influence on ground or surface water outside mine areas reported or implied.

North Dakota

In contrast to the operations in Montana and Wyoming, all the mine sites studied in western North Dakota are located in ground-water recharge areas. The mine sites are located on hills, ridges, or broad uplands that are generally flanked by deeply incised glacial melt-water channels or preglacial valleys. Thus, the coal aquifers being mined have a limited lateral extent and are not connected to more widespread regional aquifers.

Both the limited lateral extent of the coal aquifers that will be mined and the topographic and hydrologic setting of mine sites tend to restrict the distance to which the water table or potentiometric surfaces can be influenced by mine dewatering. Analysis of the dewatering problem by Moran and Cherry (1978) suggests that the rate at which water levels decline and the distance at which such effects are felt are controlled by the hydraulic properties of the aquifer, by the overburden, and by the original height of the potentiometric surface in the coal aquifer at the mine face.

Coal seams are characterized by fracture permeability that results in moderately high transmissivity but low storage capacity. The extent of the zone of significant drawdown is kept to a minimum only by the leakage of ground water downward through the overburden into the coal. The rate of vertical leakage increases in response to an increase in the vertical hydraulic gradient in the overburden caused by the drawdown in the coal aquifer (Moran and Cherry 1978). In most of western North Dakota, overburden materials apparently supply adequate leakage of recharge water to reduce the need for extensive dewatering.

Where mines are opened along or near the cropline of the coal, as is generally the case in North Dakota, the overburden is usually thin and the potentiometric surface of the coal aquifer is within or just above the coal seam. As a result, the initial decline in water level at the drainage face is small, generally not more than a few meters, and dewatering effects are correspondingly minor. On the other hand, where the initial mine cut is made in areas of thick overburden, the initial decline in the potentiometric surface at the drainage face may be as much as 20 meters. In such a case, water levels in wells are expected to be strongly affected at considerably greater distances from the mine site.

Using the Falkirk site as an example, Moran and Cherry (1978) calculated potentiometric declines for an initial cut in each of the

two settings. For the cropline cut, the dewatering curve extends 2
3 km from the highwall and the drawdown is less than 1 m at 1 to 1.
from the highwall. The curve is expected to change with the advanc
pit and, as a result, wells are not expected to show the effects of
dewatering until the mine advances to within 1 to 2 km of a well. T
second initial cut that was evaluated resulted in an initial declin
about 16 m in the potentiometric surface in the Hagel seam. The
decline was projected to cause extensive dewatering of the coal aqu
to a distance of about 4 km on either side of the mine pit. Althou
little information exists on the hydrologic properties of overburde
cast by dragline, some studies suggest that, in some places, mine
spoils may be able to meet most of the water-quantity requirements
post-mining agricultural uses.

As a result of dragline emplacement of the spoils and contouri
bulldozers, most mines in the Northern Great Plains Province have
zone of coarse, blocky rubble that accumulates in the base of the
pit. The rubble zone is overlain by fine-grained spoil materials.
Studies made throughout the Northern Plains Province suggest that
greater permeability of the basal rubble zone makes it an aquifer
is similar in most respects to the coal aquifer being replaced (Va
Voast and others 1978, Groenewold 1979, Groenewold and Bailey 1979

In most mined areas, water reenters the cast overburden rapidl
with as much as 5 to 10 m of saturated thickness developing within
5 years (Montana Bureau of Mines and Geology and U.S. Geological S
1978; Van Voast and others 1978). Given the recharge rates for th
region, which are about 2 cm/year, this amount of resaturation is
several orders of magnitude too great to be attributed to infiltra
from the surface. Rather, the resaturation appears to occur by la
flow from unmined aquifers and from older spoil materials (Groenew
1979). In some cases, recharge has been attributed to surface-wat
the spoil, such as that which occurs at the Big Sky Mine in Montan
(Van Voast and others 1978).

Rocky Mountain Province

Observed effects in the Rocky Mountain Province center around
surface mining in Colorado, New Mexico, and Arizona and undergroun
mining in Colorado and Utah. Surface-mining operations are condu
in Representative Settings A and B (Figures 4.5a and b), and
underground mining operations are primarily in Representative Set
A, B, C, and D (Figures 4.5a, b, c, and d).

Colorado

extensive study has been done by Hounslow and others (1978) at the Energy Fuels Mine, located about 3 miles north of the Edna Mine.

Edna Mine. The Edna mine has been operating since 1947 and has disturbed about 1,800 acres of land. In the currently active part of the mine, no water is being encountered (McWhorter and others 1979). In spoils from earlier mining, ground water is present and drains into Trout Creek, a perennial stream along the down-gradient side of the mine. Extensive sampling and interpretation by McWhorter and his colleagues have found that the seepage of Edna mine waters into Trout Creek causes substantially increased dissolved-solids content in stream flow. The amount of increase depends on seasonal conditions. A four-fold increase was found during certain times of the year, such as early spring, when ground-water discharge was substantial from spoils but dilution from higher elevation snow melt had not yet begun. Part of the water-quality degradation is caused by physical differences between bedrock and spoils. The more permeable mine spoils allow deeper percolation of rainfall and snow melt, significantly increasing the potential for dissolution of salts.

Energy Fuels Mine. The hydrogeologic conditions of the Energy Fuels mine and the Edna mine are similar. Consistent with most other mine areas, the water in and draining from the Energy Fuels mine spoils is much more highly mineralized than nearby surface and ground water. Analyses by Hounslow and others (1978) found that water associated with the spoils had total dissolved-solids contents approximately six times higher than those in surface water upstream from the mine; predominant ions were calcium and sulfate. The influence of the waters on the offsite stream flow and ground-water quality is not known.

Utah

Surface mining of coal in Utah is not in an active phase; however, in southern Utah, mining of the Henry Mountain, Kaiparowits Plateau, Alton, and Kolob coal resources are being considered (USDI 1979). The impact statement specifically addressed the potential effects of mining the Alton coal and slurrying it to generating plants outside the area. The planned contour operation would remove low-permeability overburden. The impact statement concluded that sodium, sulfate, and nitrate would increase in the ground water in and near the mine area. For the long term, withdrawal of water from the Navajo sandstone for industrial supply would increase pumping depths by more than 100 ft. However, the effect of mining on the near-surface ground-water system and Navajo sandstone aquifer would be localized and would not have a significant impact on the Colorado River system.

Colorado and Utah Underground Mining

Basinwide effects of underground mining on ground- or surface-w quality is generally negligible despite localized problems. Acid m drainage from some underground mines may be possible; however, spec cases have not yet been identified. Alkaline mine waters with a pH 12.2 and a total dissolved solids of 3,030 mg/l have been found in target seam at the proposed Rienau No. 2 mine near Meeker, Colorado although flows are not significant. In Utah, the dissolved solids the Emery Deep mine discharge exceed 5,000 mg/l, and in the Sunnysi mine discharge, they exceed 1,000 mg/l. Otherwise, total dissolved solids averages 500 mg/l or less.

The potential for water quality to be affected regionwide by underground coal mining thus appears to be negligible. The followi points support this conclusion:

(1) Ground water in the region is frequently chemically well buffered against acid-forming processes by the frequency of carbona occurrence within the hydrochemical system. Calcium carbonate is a common cementing agent in many sedimentary units in the West and is usually associated with ground water.

(2) Interrupted ground-water systems are generally localized wi documented ground-water discharges from underground coal mines in t region consisting of low flow volumes. In conjunction with water-quality discharge restrictions placed on mine operators by OS EPA, and state regulatory agencies, the total effect is one of minc discharges that generally meet all appropriate water-quality standa

In most areas, where underground mining occurs beneath thick overburden, ground water in affected aquifers is not used. In some cases, mines operate near major springs where dewatering may be a future problem, particularly around the Deer Creek Mine near Huntington, Utah and around the Emery Coal Field in Utah.

Virtually no data exist on drawdown effects around mines in the Wasatch Plateau, Book Cliffs, or other areas of deep cover. Howeve the nature of the Blackhawk formation and other cretaceous formatic makes large-scale drawdown unlikely. Because of the inconsistent interbedding and low hydraulic conductivities of sandstones, shale and coals within the coal regions, many local, semiperched ground-w systems may be created, and significant hydraulic interconnections infrequent. So long as major aquifers are not substantially influe by mining operations, impacts should be localized and major impact beyond the immediate vicinity of the mine are unlikely.

A notable exception may occur in eastern Utah where several municipalities could have their water supplies affected. Some town arid valle s have ap ropriated rights to spring flows in the nearb

al dissolved-solids content of 759 mg/l (USGS 1978b). The Emery p mine, 3 miles from the well, experienced an inflow of about 0.67 ic feet per second (430,000 gpd), and the flow is increasing with e (Consolidation Coal Company 1979). Projected mining is up dient and toward the town of Emery. Studies to date do not project acts for the town water supply, but research is continuing.

To generalize potential impacts on a larger scale would be ccurate because of the local occurrence of most potentially affected und-water systems. Stratigraphic and associated hydrogeologic racteristics vary considerably, both laterally and vertically, and al jointing and fracturing also appear to play a major role in und-water movement in the coal regions. Therefore, accurate dictions of effects will require site-specific study in each case.

Subsidence at certain underground coal mine areas in Colorado and h has been investigated by Dunrud (1976), Osterwald and others 71), Osterwald and others (1972), and by some coal mining panies. The U.S. Geological Survey (1978a) has published a review subsidence effects in the western Powder River basin, and a review subsidence effects around Sheridan, Wyoming, is in press. The work Dunrud (1976) most clearly outlines some potential hydrogeologic ects of subsidence related to underground coal mining. The effects ically relate to the interception of spring flow, ground-water flow, stream flow by subsidence cracks, which channel water to deeper ata or the abandoned mine. The Oliver No. 2 mine, located in the coal beds south of the North Fork Gunnison River in Colorado, is a r example of significant hydrogeologic effects from subsidence nrud 1976). Dunrud (1979, personal communication, U.S. Geological vey, Denver, Colorado) also reports that several springs above the nyside mine in Utah have dried up following subsidence in that . In the same area, vegetation near surface cracks is dying due to atering. Dunrud (1976) has reported that above the Geneva mine, th of the Sunnyside mine, large tension cracks, hundreds of feet g and from 0.06 in. to 3 ft. in width formed in Mesaverde group ks in an area of 900 ft. of cover. Dunrud also observed that some the wider cracks emitted air from mine workings, indicating that the cks connected the mine with the ground surface. The cracks divert surface- and ground-water flow in the area to lower strata or to mine workings. Tension cracks of up to 1 ft. in width have eared above the Somerset mine in Colorado. Several decades ago, a l mine in shallow cover under Clear Creek, near Golden, Colorado, flooded when stream flow was intercepted by subsidence cracks (T. r, 1979, personal communication, U.S. Geological Survey, Water ources Division, Denver, Colorado).

Currently, the mining industry is being required to initiate veyed subsidence studies. The data have yet to be formally

springs and aquifers, and perhaps interception of stream flow, has been observed at selected mines in Utah and Colorado. Methods for predicting subsidence and its hydrologic effects have yet to be outlined in the literature.

New Mexico and Arizona

The effects of surface mining in the Southwest relate to operations in New Mexico (Navajo mine, McKinley mine, and Branham mine) and Arizona (Black Mesa mine). In those operations, coal is surface-mined from cretaceous formations that contain zones of perched ground water. Alluvial material forms a near-surface aquifer that, when saturated, is usually the sole source of domestic water supply in the area (USDI 1976). Sandstones underlying the coal are utilized for municipal and industrial water supplies.

Overburden and spoil analyses at the Navajo mine indicate sodium and chloride are available soluable salts that would be the principal components in surface runoff, resaturation, and deep percolation (McWhorter and others 1975). Old spoils at the McKinley site, in which surface runoff had pooled, showed resaturation occurring as a sodium-sulfate water (Hounslow and others 1978). New spoils are being covered with soil materials that are expected to reduce the infiltration of water. The total dissolved-solids content of water in areas of resaturated spoils are expected to range between 2,000 mg/l and 4,000 mg/l (Hinton 1980, personal communication, Pittsburgh-Midway Coal of Gulf, Denver, Colorado). Research efforts by the Bureau of Land Management of the Bisti EMRIA concluded that, if resaturation occurred from increased recharge and upward leakage from the Picture Cliffs sandstone, water quality would be a sodium-sulfate type with total dissolved-solids content of about 4,000 mg/l, similar to the Picture Cliffs aquifer, and that the coal-seam aquifer would be destroyed as a source of good quality water (USDI 1976). The hydrologic regime of arroyos in the arid Southwest and the subsequent hydrogeologic effects of mining operations has not been clearly defined (J. Hinton 1980, personal communication, Pittsburgh-Midway Coal of Gulf, Denver, Colorado).

Post-mining effects on water quantity and quality in Arizona and New Mexico are not well documented. Where water has resaturated portions of spoil, the water is a sodium-sulfate type with a total dissolved-solids content of well over 1,000 mg/l.

Pacific Coast Province

Most coal mining in the Pacific Coast Province takes place in Washington. Mining is conducted under conditions similar to that depicted by Representative Settings A and C (Figures 4.9a and c).

The only data available on the effect of mining on the ground-water reservoirs in the Pacific Coast Province were derived from a discussion with the engineering geologist of The Washington Irrigation and Development Company, operators of the Centralia mine (R. Paul 1980, personal communication, Washington Irrigation and Development Company, Centralia, Washington).

The mine is a surface-mine operation with a 5,000-ft. working front. Coal, which is mined from the tertiary Skookumchuck formation, is saturated in the area and has low permeability. Clays associated with the coal are bentonitic. During mining, pits are pumped to remove runoff and small amounts of ground water. Spoil material includes overburden, solids from the coal-cleaning facility, and some fly ash. A consulting study that evaluated the post-mining hydrology showed that the spoils were resaturating and receiving recharge. Analyses of post-mining ground-water quality showed total dissolved-solids values of 350 to 4,500 mg/l. Additional ground-water quality data were not available.

Principal water supplies in the area are obtained from surface water and from volcanic aquifers. The coal-bearing formation will yield water to domestic wells; however, objectionable sulfur odor has resulted in the use of surface water supplied by small water companies to rural areas. Although no detailed study of the effect of mining on the ground-water resources has been performed, the Washington Irrigation and Development Company views the control and quality of surface-water runoff (which results from the average 50 in. of rain per year) as its major concern.

GROUND-WATER-RELATED IMPACTS OF COAL MINING

The quantity and quality of ground-water resources will sooner or later influence all living things, either directly or indirectly. Thus, when coal mining or any other activity alters ground-water resources, it also indirectly causes changes in the lives of plants and animals, including humans. The changes are referred to here as "impacts" and are sometimes separated into ecological (nonhuman) and social or socioeconomic (human) impacts.

Impacts are neither good nor bad in themselves. They are simply changes. Reference to beneficial and adverse impacts implies not only the characteristics and magnitudes of the impacts themselves but also the subjective appraisals as to whether the impacts are desirable or undesirable. Such appraisals may differ in magnitude and even in direction. Few would disagree that to increase ground-water supplies in an arid area would be a beneficial impact, although there could be disagreement about just how beneficial such an increase would be. Similarly, few would disagree that to introduce toxic substances into a ground-water system would be an adverse impact, although those who rely on that resource for potable water supplies might believe it to be more serious than those who do not.

Impacts seldom are discussed in an objective, value-free way. More

must be incorporated before a decision can be made about whether to increase or decrease an impact or how much action is appropriate. Such actions always entail costs, and whether the costs are worth incurring cannot be known without comparing them to the sum of the associated benefits that would result. Each benefit is the product of the impact and the value placed upon it by those who are affected.

Determining the value of impacts, or changes in impacts, is no less difficult than estimating the characters and magnitudes of the impacts in the first place. Certain impacts, because they are exchanged in the economic marketplace, acquire prices that represent just one measure of value. However, virtually all impacts are appraised by someone at some time by other value measures. Many analytical techniques are available to make such appraisals explicit and even commensurate. None is beyond objection, and all techniques require the ultimate political judgment of differing appraisals by different persons.

The committee was unable to provide a systematic, comprehensive, and reliable description of all the ground-water-related impacts that coal mining has produced in the past or is now producing. The data needed to reveal all existing impacts in a comprehensive manner do not exist. Projecting impacts of future coal mining is even more difficult, because the committee cannot predict how much or what kind of coal mining will occur in the future or where it will occur. However, certain impacts that have occurred and that are attributable to the ground-water effects of coal mining can be described. Thus, illustrations can be made of the kinds of impacts that may be controlled by public policy.

Acid Mine Drainage

In 1969, the Appalachian Regional Commission reported that acid mine drainage had affected the water quality of 5,700 miles of streams in Appalachia (Appalachian Regional Commission 1969). In the Susquehanna, Allegheny, Potomac, Delaware, and Monongahela River basins alone, some 4,300 miles, or 8.5 percent, of the total stream mileage, were affected. The worst problems were in Pennsylvania and West Virginia. Underground coal mines produced about 70 percent of acid mine drainage in Appalachia, and abandoned mines, both underground and surface, were responsible for about 80 percent of the problems.

The Appalachian Regional Commission's economic analysis of acid mine drainage found that acid water slightly increases the costs of industries that use it but that adaptation of the water, rather than avoidance of its use or relocation of industries, has been the rule. The Commission also found that the presence of acid mine drainage apparently has not affected the location of highways and navigation operations in Appalachia. The commission estimated that annual benefits of $4,230,000 would accrue to industry, transportation, and municipal water supply if acid mine drainage was reduced by 90 percent (Appalachian Regional Commission 1969).

Recreation is severely constrained by acid water conditions, but the commission's analysis did not indicate benefits to recreation because such estimates are difficult to make. However, a study of the southwestern Pennsylvania area, where water-based recreational demand is great, estimated that annual benefits of $25 million would result from control of acid mine drainage. During the time the study was made, Pennsylvania had committed $150 million for control of such drainage, or about 16 percent of the total capital costs estimated for a 10-year abatement program. Despite such projected large benefits to recreation, the Appalachian Regional Commission concluded that because of high control costs, the abatement of acid mine drainage could be justified for recreation alone only when alternative recreational sites and facilities were not available. The U.S. Department of the Interior estimated that, at the time of the commission's study, capital costs for controlling and abating acid mine drainage for the nation over a 20-year period would be $6.6 billion, in addition to significant annual maintenance costs.

Because of the age of the Appalachian Regional Commission Study and the implementation of acid mine drainage controls during this time period, it is expected that the statistics which have been quoted have changed substantially. At least 12 years have passed since the original data were compiled for this study. During this same time, state and federal water quality laws have been implemented to control discharges from active mining operations while at the same time funds have been allocated for abandoned land reclamation. To date, no effort has been made on the level of the 1969 Appalachian Regional Commission Study to document the effectiveness of these programs. Consequently, we are unable to report on the current status of acid mine drainage effects in the eastern coal region.

Depletion of Shallow Ground Water

Large-scale surface mining is occurring in the Northern Great Plains and is expected to expand rapidly. Such mining disrupts and dewaters shallow aquifers in the vicinity of mines. In the Northern Great Plains, shallow ground waters are currently used for livestock and rural domestic needs but are generally insufficient for industrial needs. A surface-mining operation can affect ground-water levels within 3 or 4 miles of the cut. At deeper surface mines, water levels may be lowered as much as 200 or 300 ft. The water-table level will, for the most part, reestablish itself when mining activities stop. Wells within the area of influence will be wholly or partially dewatered, but may be replenished by drilling to deeper aquifers. In some locations, the new depth may be down to 500 ft. The water will usually be of equivalent quality. If well water is not replaced, the population that resides in the area of disruption will experience severe social imports, because in most instances they will be without water for livestock or domestic use.

When shallow aquifers are dewatered, spring flow will be depleted

provide drinking water for wildlife or create special habitat conditions, and, thus, dewatering could potentially affect wildlife populations in the areas. Where augmentation of stream flow and stream underflow is reduced because of the lowering of the water table and the lack of discharge into streams from underground sources, aquatic life will be affected as well (Northern Great Plains Resources Program 1974).

Reclamation of Mined Land

An objective of reclaming mined land, as currently practiced, is to produce a land surface that will be as productive as or more productive than it was before mining occurred. At present, no known reclamation design of mined land attempts to minimize the degradation of ground-water quality or to influence the subsurface hydrological system.

In the West, particularly in the Fort Union coal district, mine spoil contains soluble sulfate salts, exchangeable sodium on the clay fraction of the sediment, and reduced sulfur that can oxidize to produce more sulfate salt and sodium from exchange sites in solution. When infiltration causes those constituents to be transported from the spoil downward to the water table, deterioration of ground-water quality will occur.

Soluble salts, the exchangeable sodium, and oxidizable reduced sulfur are sources of dissolved constituents that can also cause deterioration in the agricultural productivity of the soil zone, as when spoil that has excessive concentrations of the constituents occurs close to the root zone (i.e., at shallow depths below the topsoil). In areas such as most of the eastern United States, infiltration occurs in sufficient quantity to cause the salts to be carried to considerable depths away from the soil and root zone. In areas where infiltration is infrequent or generally occurs with insufficient intensity to cause the water to move rapidly to a depth far below the soil zone, as is typical of parts of the West, dissolved salts and exchangeable sodium from the spoil located below the topsoil can move upward into the root zone. The upward movement occurs because of temporary upward hydraulic gradients, thermal gradients, or chemical or osmotic gradients.

Excessive sodium in soil is particularly harmful to agricultural productivity in the Northern Great Plains because the sodium causes swelling of clay minerals common in the area, impeding the movement of water and air into the root zone. The condition may take years to develop and may produce only sporadic symptoms; however, its long-term impacts are deleterious to crop production and are virtually irreversible. Therefore, any attempt at reclamation of mined land to minimize deterioration of ground-water quality must also take into account the potential for deterioration of soil productivity.

SUMMARY OF IMPACTS

The discussion of effects and consequent impacts that coal mining

was intended to be illustrative and suggestive, and to bring out the following points.

1. Lowering of water tables commonly occurs locally as a result of coal mining. The cone of depression is confined to the vicinity of the mine, but is highly variable, depending on hydrogeologic conditions. Lowering of the water table in turn often causes adverse impacts on ground-water users within the area affected. Some wells may be dried up and others may require increased pumping costs to raise the water from greater depths. Springs and seeps fed by ground water may cease to flow, causing adverse impacts on ecosystems.

   The adverse social and ecological impacts produced by water-table reductions due to present coal mining are both locally confined and usually temporary in nature. They do not constitute a major social cost, although on occasion they may have been quite costly to a few individuals. The impacts of coal mining to date have been virtually insignificant compared to the effects that the lowering of water tables from agricultural use has caused in the high plains of Texas and Oklahoma or in the central valley of California.

   In the future, as coal mining expands in the arid and semi-arid West, the possibility of substantial adverse effects from water table lowering caused by mining will increase, so that this may become a major problem in the future. Ground-water resources in the West are far more limited than in the East. Recharge rates are generally lower as well. Also, the scale of mining contemplated for some western areas could produce water-table lowering throughout extensive areas, so that what currently is a local problem conceivably could become a regional one in the future. And, in some instances, the changes in hydrogeologic structure that could be produced by large surface mines could cause permanent changes in water-table levels. (In some situations, the level of a water table could be raised rather than lowered.)

   Although more serious future impacts from water-table lowering because of coal mining are possible, particularly in the West, three qualifying considerations should be kept in mind: First, coal mining by itself is not a major user of either ground or surface water. It does not and will not often deplete water supplies important to other users, even though it may produce water-table lowering generally temporary and local in effect. (Converting coal into other energy forms and, in places, reclaiming mined lands may require substantial amounts of water, but such activities are beyond the scope of this report.) Second, human populations are sparse and widely scattered in much of the West, so that the potential for adverse social impacts is less than in the more densely populated East. Third, the impacts due to water-table lowering are among the easiest and cheapest to mitigate (see

2. Water-quality degradation can be and has been caused by coal mining. Acid mine drainage continues to be a problem in the East, and ecological impacts have been severe, with much destruction of riparian habitat. In the West, owing to different hydrogeologic and soil conditions, the problem is one of salinity and alkalinity rather than acidity. There, water-quality degradation has been much less severe and more locally limited than acid mine drainage in the East.

   Acid mine drainage is a problem largely associated with past mining activities. Because control technology is employed in current mining, the problem should not increase greatly in importance. However, major effects will continue from past mining operations until remedial measures are taken.

   By contrast, the effects of salinity and alkalinity in the West might grow in severity in the future, unless the pace of development and implementation of impact-control technology is quickened. Impacts on agriculture in the Northern Great Plains will probably be the most serious, because coal and crop production are uses that will become increasingly competitive for both land and water. Elsewhere, local ecological impacts will no doubt be felt, but the effects of coal mining on ground-water quality seem unlikely to become a serious problem.

   An exception to this optimistic assessment could occur if underground coal gasification develops on a major scale and if means for controlling the potential introduction of toxic byproducts of underground combustion into ground-water supplies are not developed and implemented. Important ground-water resources could be rendered indefinitely unusable in this case, producing impacts which could be the most costly and long-lasting of any of the impacts to ground water from coal mining.

3. Ground-water impacts from coal mining can be expected to increase in the future. This conclusion follows almost necessarily from the anticipated sharp acceleration in the pace of coal mining activity and from a parallel increase in reliance on ground water to supply the nation's water demands. There will be greater mining activity to cause effects and impacts, and there will be more reliance on ground water which will increase the severity or cost of impacts. This appraisal applies to potential future impacts, however. Careful policy making and planning, including the development and application of impact-control technology, could avoid, forestall, or ameliorate many potential impacts.

   Complete avoidance of adverse impacts and costs is neither a sensible nor a possible policy goal. Any activity that produces benefits also entails costs. Costs and impacts may be reduced, but they cannot be eliminated except by eliminating the benefits as well. Finding the proper balance, where benefits exceed costs by the gre e m gin, is e

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CHAPTER 6

RECOMMENDED METHODS FOR IDENTIFICATION AND PREDICTION OF EFFECTS

INTRODUCTION

Methods of identifying the effects of mining on ground water have been developed over several decades, and standard techniques are available for assessing basic hydrogeologic parameters. However, new techniques are currently being researched in response to a need for assessments of the potential for contamination of ground-water resources from waste disposal activities. Moreover, in many situations, new field methods and tools are needed for investigations of the effects of coal mining on ground-water quality. Because ground-water studies are costly, relatively inexpensive techniques for acquiring data need to be developed. Methods of predicting effects in the field are especially important, because ground-water models, the standard predictive tools, require a large number of field data in order to be accurate.

This chapter discusses the current status of methods to identify and predict effects on ground water. Coal mining is used as the example of an activity that can cause effects on ground water.

IDENTIFICATION OF EFFECTS

In order to identify and predict the effects of coal mining on ground water, the pre-mining, mining, and post-mining hydrologic conditions of a site must be thoroughly described. This information is generally collected in stages (Figure 6.1). The first step in a hydrogeologic investigation is to compile, analyze, and interpret all geological and hydrological information available on the site and its environs. The geological information normally consists of stratigraphic data from borehole logs and water well records, logs of boreholes drilled during coal exploration or reserve evaluation, geological maps of surface features, aerial photographs and soil maps, and, when available, data on the mineralogical composition of the overburden deposits. The hydrological information usually consists of well records indicating depths of water wells and, in some cases, of

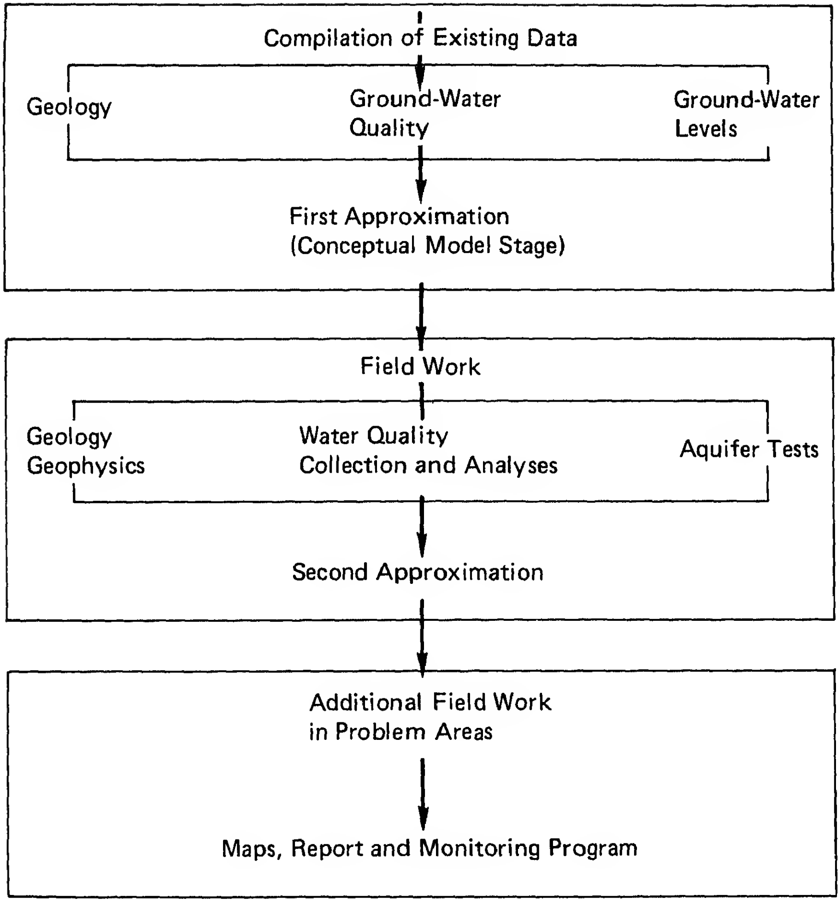

FIGURE 6.1 A Conceptual Approach to Hydrogeologic Investigations

static water levels in the wells; flow records for major streams or rivers; precipitation records; and any reports by federal or state agencies on regional hydrogeological features.

Information on water resources is collected by many different agencies at all levels of government. At the federal level, the Department of the Interior's U.S. Geological Survey (USGS) acquires a large percentage of the nation's water data. The USGS maintains a national network for acquiring and cataloging data on the quality and quantity of surface and ground water. Data handling is facilitated with the National Water Data Exchange (NAWDEX). NAWDEX consists of member organizations which exchange information on various aspects of water. The NAWDEX system indexes all current data collection sites. The index includes types of data collected at each site, the dates the data were collected, and the agency that provided the information.

The USGS also maintains a massive data file called WATSTORE (National Water Data Storage and Retrieval System). WATSTORE is a series of crosslinked data files containing information on ground-water and surface-water quantity and quality. The Environmental Protection Agency (EPA) maintains a computer file of water-quality data known as STORET.

Water data files in state agencies generally are maintained by the state geological survey office or the state natural resources department. To date, few states maintain centralized, accessible data-storage files. Thus, many data (such as drilling logs of water wells) useful for evaluating subsurface geologic and hydrologic conditions, and which cover wide areas, are not readily available away from the particular state agency office.

Despite the federal and state data collection efforts, the existing geological and hydrological information usually provides only a general impression of the ground-water conditions at a site. The information is rarely complete enough to provide very specific or detailed descriptions of site conditions or predictions of the influence of activities, such as coal mining, on ground-water flow and quality. In most situations, the compilation and interpretation of existing information on a site provide merely a basis for the design of a site-specific program of investigation. From such a site-specific study, the existing hydrological and geological conditions can be determined, and predictions of changes that may occur as a result of activities, such as coal mining, can then be developed.

A site investigation almost invariably requires geological test drilling in order to gain a better understanding of the subsurface geological conditions. Observation wells or piezometers are installed to monitor levels of ground water in the area and to provide for collection of ground-water samples for chemical analyses. Along with or prior to the program of geological drilling and installation of observation wells, existing water-supply wells are usually inventoried (i.e., information on their existence, depth, and usage is gathered) and, in some cases, the wells are sampled for water-quality analyses. Although numerous wells for domestic or agricultural use may exist in an area, detailed information on the geology and pumping interval for

program of drilling, well installation, and sampling, a survey and sampling of surface features of hydrogeological interest are usually conducted. The features include springs, seeps, marshes, baseflow conditions of streams and rivers, and, in some areas in the West, areas of saline soil and surface salt accumulation. The temperature, electrical conductance, and chemical composition of springs, seeps, and other surface hydrological features can aid in the development of a reliable interpretation of the ground-water conditions in the area.

The number and depths of boreholes and observation wells necessary to provide an adequate understanding of the ground-water system depends on the degree of geological complexity of the site and the nature of the proposed or existing activity that motivated the investigation. For example, in the case of coal mining, the number of boreholes and wells would depend on the area and depth of the proposed mine. No general rule can be applied in this regard, although Peek (1980) suggested some general empiricial guidelines.

In order to delineate the geological conditions, a geologist inspects and describes the borehole cuttings and core samples; in addition, the boreholes may need to be logged by geophysical methods. Geophysical measurements made at the surface using seismic, resistivity, and gravity methods can also provide useful information. Information obtained from observation wells can be supplemented by pumping tests to achieve a better understanding of the hydraulic conductivity and continuity of critical zones in the ground-water system.

At this stage of an investigation, the conceptual model developed through the initial literature search has now been refined and is a fairly good representation of the hydrogeologic framework of the site. Based on the geologic, topographic, and hydrologic information, the expected ground-water direction and flow rate can be determined. The position of the coal mine, waste disposal site, or well within the local and regional flow systems can also be determined, including the relationship to zones of ground-water recharge and discharge. This information can be used to construct soil maps and to design a monitoring program.

Observation Wells

An adequate number of wells are needed in each aquifer to construct water-level maps. Normally, some wells are located on the up-gradient side of a coal mine or waste disposal area within each aquifer likely to be affected. The wells can provide information on the quality of the water entering the site. Some wells are also needed on the down-gradient side of a coal mine or waste disposal area to determine the water level in each aquifer and to document the quality of the ground water after it has passed through the site. Additional wells are placed near hydrologic boundaries, flow discontinuities, or other critical areas, such as (1) zones of ground-water recharge or discharge; (2) regions up gradient of important water-supply wells; (3)

locations near mine shafts, pits, or tunnels; (4) areas along surface bodies of water; or (5) regions in the vicinity of other types of geologic discontinuities (faults, folds, changes in aquifer thickness, etc.). The data are then used to construct water-level maps from which the hydrogeologic conditions of the site, including the direction and the rate of ground-water flow, can be inferred.

Care must be taken to ensure that wells are completed in ways that provide hydrologic data specific to the problems under study. Pertinent aquifers must be open to the wells, and other sources must be sealed off. To ensure dependable data, the drilling and installations should be supervised by hydrogeologists responsible for the research.

Water Levels

Regular monitoring of water levels in observation wells is used to determine the effects of coal mining and reclamation, waste disposal, or pumping on the direction and magnitude of ground-water flow. Water levels are used to prepare maps showing the ground-water flow conditions. In the case of coal mining, measurements made during mining and reclamation are used to determine changes in the pattern of flow and to predict future hydrologic impacts. Continued monitoring after reclamation can also be used to determine the long-term effects of coal mining.

Aquifer Tests

Tests of the hydrologic characteristics of aquifers in the vicinity of the coal mine or waste disposal sites determine how well the aquifers store and transmit water. The test can determine such things as the amount of water that will have to be pumped from mine pits or tunnels and the rate at which chemically altered water may move away from the site.

The most widely used method for determining the storage and transmission properties of an aquifer is a pumping test. This test may be conducted in a single pumping well or observation well or in a pumping well and a series of observation wells. Pumping tests are conducted by pumping at a constant rate or in a series of stepped rates. Alternatively, the water level in a well may be changed instantaneously by adding or removing a slug of water (slug test). Theoretically, the change in water level over time can be used to determine the transmission properties (transmissivity) and storage characteristics (storage coefficient) of an aquifer. Often, aquifers associated with coal deposits have low transmissivities and are extremely sensitive to slight changes in pumping rates. The aquifers can be tested more reliably by noting the recovery rate of water levels after pumping ceases. Other methods for determining aquifer characteristics are shown in Table 6.1. The methods are based on explicit assumptions regarding both the homogeneity and extent of the

Test	Reference	Major Items Required	Parameters Obtained*	Comments
Pumping	USDI 1977; Lohman 1972. Stallman 1971; Walton 1962; Ferris & Knowles 1963; Ferris et al. 1962.	Minimum of one observation well and preferably 4 or more; pump; power source; winch; tripod, mast or boom; discharge measuring device; stop watch; water level sounder.	T,K,S	Yields parameter values averaged over a relatively large aquifer volume; most commonly used when accuracy and reliability is of high priority; best results in aquifers with good continuity and permeability provided by intergranular flow channels; can provide evidence of leakage through aquitards, directional permeability, and the presence of hydrogeologic boundaries. -Relatively expensive, doesn't work well in very tight aquifers, requires a power source.
Drawdown/ specific capacity	USDI 1977; Lohman 1977; Walton 1970.	Same as above, but no observation wells are required.	T,K	Yields only rough estimates of T and/or K; storage coefficient or apparent specific yield must be estimated independently; conditions immediately adjacent to the well bore, well losses, etc. substantially effect results; in tight aquifers the effects of well-bore storage may be highly important. -Relatively inexpensive; most useful in reconnaissance investigations.
Gravity injection	Same as above.	Supply of water (water truck or tank), injection hose or tubing, in-line flow meter, water-level measuring device, stop watch.	T,K	Can be conducted on cased or open holes using the same equations as those for tests described above; conducted with constant head or with constant injection rate; best applications are with clean wells in poorly transmissive materials.
Pressure pump-in	USDI 1977.	Inflatable or compression packers; pump; power source; pressure gages; stop watch; in-line discharge measuring device; storage capacity and source for water.	T,K	Usually conducted during exploration or reconnaissance investigations; permits determination of T and K in different intervals along the well bore; can be used above or below the water table or water level in the well; works best in consolidated aquifers or perforated well casing. -Relatively expensive because it is usually conducted during the drilling operations using the contractors rig and equipment.
Auger hole	Boast & Kirtham 1971.	Small pump or bail; stop watch; float.	K	Applicable in cases of unconfined aquifers when the water table is within a few feet of ground surface; inexpensive, rapid, reliable.
Recovery after any of the above tests.	Same as for test.	Same as for test.	T,K,S	Recovery should always be monitored following a drawdown/specific capacity test; usually yields more reliable values for T and K than the drawdown/ specific capacity test; has the additional advantage of providing an estimate of storage coefficient or apparent specific yield; because the rate of recovery is dependent upon the preceding pumping rate the results are affected by well-bore storage. -Minimum expense in addition to that incurred during the pumping period and provides additional and more reliable information than the drawdown/specific capacity test.
Slug/falling head recovery	USDI 1977; Lohman 1972; Ferris & Knowles 1963; Kvorslev 1951; Covack & Papadopulos 1967; Bouwer 1978.	Equipment required depends upon the manner in which the slug is added or removed. Pump may be used but it is not required.	T,K	A specific type of recovery test; one of the simplest and least expensive of all tests; does not require a power source; yields values acceptably accurate for most purposes; analysis procedures available that account for aquifer storage only, well-bore storage only, or both. Applicable in both confined and unconfined aquifers.

*T = transmissivity, K = hydraulic conductivity, S = storage coefficient or specific yield.

Source: Modified from McWhorter et al. 1979.

conditions assumed to exist are ensured or closely approximated.

Water-Quality Measurements

Contaminants can be transported in ground water by three different mechanisms--advection, dispersion, and diffusion. Advection refers to movement caused by differences in water levels. Dispersion refers to mixing and spreading caused on a microscopic scale by flow around individual grains in the porous material and on a macroscopic scale by flow around large-scale heterogenities. Diffusion is flow induced by differences in concentrations of chemical constituents. Because water movement through porous media invariably causes a certain amount of dispersion or spreading of the contaminants, monitoring wells are located in areas where detection of changes is most likely to be possible. Monitoring begins prior to siting the mine or waste disposal area and extends through operation and reclamation. Samples are collected throughout the year so that normal seasonal variations can separated from effects caused by mining or waste disposal. Sampling frequency for any particular well is dependent in part on the probability that the aquifer will be contaminated. For aquifers that are isolated or have only a slight probability of being affected, sampling may be necessary only once or twice yearly. Aquifers in positions likely to be affected or whose hydraulic conductivity allows rapid movement of water should be sampled monthly.

Water standing in a well most often is not representative of the water in the aquifer because chemical changes may occur within the well if water is static for a long time. Three volumes of water at least equal to that standing in the well casing should be removed from the well before samples are collected to ensure that the samples reflect the quality of the water in the aquifer.

Standard or recommended practices should be followed for sample handling and preservation. Some water-quality parameters, such as acidity/alkalinity, specific conductivity, and pH, change rapidly and should be measured in the field. Samples taken to a laboratory for further testing should be preserved and analyzed according to the current guidelines of the U.S. Environmental Protection Agency (1974).

For coal-related studies, the mineral analyses include determinations of total suspended and dissolved solids, total iron, pH, and total manganese. Several state regulatory agencies require additional testing. Further analyses may be warranted when important water sources will be involved.

Monitoring Wells

Correct design and placement of monitoring wells are essential for the proper evaluation of changes in hydrogeologic flow systems and ground-water quality. Haphazard plans for monitoring networks result in excessive costs and can lead to the installation of wells that fail

to meet their objectives. Monitoring wells are located only where meaningful information can be obtained. Existing data and wells are used whenever possible to minimize costs in the construction of monitoring networks. Boreholes can also serve a number of purposes; the efforts of exploration, mining, and environmental personnel are often coordinated so that new wells can provide the data required by all.

METHODOLOGY FOR PREDICTION OF EFFECTS

After the geological, geophysical, hydrological, and hydrogeochemical data from the field investigation have been compiled, and interpretations of the existing ground-water conditions at the site made, predictions of effects that may occur as a result of proposed activities (such as coal mining) are developed.

While both general and detailed predictions of effects can often be made based on what is known about existing conditions, developing detailed predictions of specific effects is difficult, and with the current state of knowledge, predictive methods are plagued with uncertainty. In the case of coal mining, predictions of changes in ground-water flow and quality and of changes in the influence of ground-water flow on surface water must be made for relatively long periods in the future. However, changes in ground-water conditions may be gradual, occurring over decades or even longer timespans. Some of the changes may be irreversible or will only reverse slowly.

Models or representations of the natural system are used to predict effects. A properly constructed ground-water model that simplifies reality can be a valuable predictive tool. Because the validity of a prediction will depend on how well the model approximates field conditions, good field data are essential when developing a model for predictive purposes. However, an attempt to model a system by using inadequate field data can help identify those areas where detailed field data are critical in order to simulate the observed behavior of the ground-water system. Thus, a model can help guide data collection activities.

Three broad categories of models have been used to study ground-water systems: physical (sand tank) models, analog models (including electric and viscous fluid models), and mathematical models (both analytical and numerical). An additional category contains conceptual models such as maps, flow charts, and experience which are qualitative or semiquantitative representations of the physical or chemical characteristics of a ground-water system. The two most commonly used models, conceptual and mathematical, are discussed in detail below. Prickett (1975) provides information on the use of sand tank and analog models.

For surface-mined lands, models are necessary to predict the effects of mining and reclamation of ground-water conditions within, below, and around the mined land. The modeling effort must consider

Conceptual models that involve diagrammatic representation of patterns of geologic site conditions, geological origin or developmen of coal environments, or regional ground-water flow in coal mine area are an indispensable means of obtaining a perspective on coal mining and its effect on ground water. For example, Caruccio and others (1977) suggested that a conceptual model based on a map of paleoenvironments would be an effective tool for estimating the areas in the eastern United States where acid mine drainage is most likely be severe. Thus, a map of paleoenvironments in the eastern United States, together with a geologic map, allows identification of many the regions having the potential to yield severe acid mine drainage neutral drainage with high sulfate concentrations. Another example would be conceptualizations represented by hand-drawn diagrams of the patterns of ground-water flow or subsurface contaminant movement in area of existing or proposed mining. The diagrams can take into account the presumed effects of geologic stratification, fractures, faults, and other complexities in a semiquantitative manner.

When the term "model" is used in the context of determining hydrologic or hydrogeochemical effects, it normally refers to a mathematical method whereby effects of adding or taking away somethi can be computed. For prediction of the effects of coal mining on ground water, four main categories of models exist: ground-water fl models, models for the chemical evolution of water in spoil (hydrogeochemical model), models for the transport of contaminants i subsurface zones (subsurface transport models), and models for effec of ground-water inputs to surface water (ground water-surface water models). The last category can have models pertaining specifically the effects of water flow on quantity or to the effects of ground-wa inputs on surface-water quality.

Mathematical Models

Ground-Water Quantity

The use of models to predict effects on ground-water quantity is accepted technique for two-dimensional applications, and several well-documented computer models are available (e.g., see Bachmat and others 1978, Prickett and Lonnquist 1971, Trescott and others 1976). Three-dimensional computer models are also available (Trescott 1975) but, to date, applications to field problems are few because good fi data in three dimensions (e.g., lateral versus horizonal gradients) needed. In order to use these models effectively, new types of observation wells, such as discussed by Pickens and others (1978), m be designed so that water-level information in three dimensions can collected inexpensively.

So far, only a few mathematical models have been used to predict the effects of coal mining on ground-water quantity. Existing applications have been directed either at (1) assessing the local or

In the first application, analytical mathematical models are routinely used to predict drawdowns as a result of pumping wells for industrial or municipal uses. Dewatering that accompanies mining when a coal seam is below the water table can be treated using analytical formulas from well hydraulics (e.g., Van Voast and Hedges 1975). Numerical models have been used to study the regional rather than localized effects of dewatering caused by coal mining. Such models include generic studies by Wilson and Hamilton (1978) and several site-specific studies in the Northern Great Plains and the Powder River basin (Riordan 1979, McIntosh 1979, Croft and others 1978, Hittman Associates, Inc. 1979). Similar models have also been used to predict the effects of dewatering caused by other types of mining, such as oil hale (Weeks and others 1974) and to predict the effects of pumping (see Prickett 1975 for references).

McWhorter and others (1979) presented a simple analytical model for predicting the change in the ground-water flow pattern after reclamation. With this model, the hydraulic conductivity of the undisturbed aquifer, the hydraulic conductivity of the spoils material, the radius of the disturbed area, and the regional flow rate are used to predict the amount of divergence of the flow lines around the spoils aquifer. The model assumes that (1) the aquifer covers a large area; (2) the flow is uniform and one dimensional at great distances from the mined area; (3) the undisturbed aquifer and the spoils aquifer are each homogeneous and isotropic; (4) the geometry of the disturbed portion of the aquifer is that of a cylinder with the axis normal to the plane of the flow and (5) the flow around the reclaimed area is two dimensional and steady.

Ground-Water Quality

The development of mathematical models to predict changes in ground-water quality is currently an area of active research. Some computer models have been developed and documented (Konikow and Bredehoeft 1978), and several models of ground-water quality have been applied to field situations (Anderson 1979).

However, the use of these models in field situations raises several problems both theoretical and practical. The theoretical difficulties include problems in solving the governing equation used in the model, controversy over the correct form of the governing equation, and problems in quantifying chemical reactions for incorporation into the odel. Field problems involve acquiring the necessary input data. Specifically, the variations in hydraulic conductivity must be quantified in more detail than is economically feasible in most field investigations. Moreover, measurement of other parameters (such as dispersivity and chemical reaction terms) required by many of the contaminant transport models is difficult; that difficulty may be partially resolved through the incorporation of stochastic structure into contaminant transport models; that is, it will probably be

Two types of models are used to simulate contaminant transport in ground water: models that simulate advection, dispersion, and chemical reactions, and models that simulate only advection and chemical reactions. The theoretical difficulties described above are pertinent to models that incorporate dispersion, and therefore, current dispersion models are not suitable for routine use in predicting ground-water-quality changes. Preliminary research applications of models to dispersion problems related to coal mining are presented in Amend and others (1976) and Homsy (1979); however, for many applications, it is unnecessary to include dispersion in the simulation. Models that include only advection and chemical reactions are described below, and problems relating to coal mining are used as examples.

In the East, the major effect on ground-water quality is acid mine drainage. Investigators at Ohio State University (Morth and others 1972, Ricca and Chow 1974) developed a mathematical model to predict daily mine-water discharge and acid loads and tested the model using data from a deep mine in southern Ohio. However, the model requires detailed input data including precipitation and pan-evaporation records, initial soil moisture conditions, initial ground-water storage conditions, oxidation rate parameters, initial acid storage, and flow and acid load coefficients.

In the West, applications of mathematical models to water-quality problems generally have dealt with predicting water-quality changes as a result of water movement through spoils. McWhorter and others (1979) presented two such mathematical models, each of which performs at a different level of complexity but neither of which includes dispersion. The more complex of the two is a simulation model that allows consideration of flow and contaminant transport through both the unsaturated and saturated zones. All chemical reactions are assumed to take place in the unsaturated zone. The following processes are considered in the model: solubility and precipitation of gypsum, chemistry of undissociated calcium and magnesium sulfate, exchange of calcium for magnesium and of calcium for sodium, the dissociation of calcium carbonate in water, the effect of sulfate and undissociated calcium sulfate and magnesium sulfate on the exchange processes. Flow is assumed to be one-dimensional in the unsaturated zone and two-dimensional in the saturated zone. The model requires detailed input data, including: (1) parameters that characterize the properties of both unsaturated and saturated zones; (2) boundary and initial conditions for flow; (3) concentrations of calcium, magnesium, sodium, chloride, bicarbonate, and sulfate in the spoil; (4) concentrations of the same species in water flowing into the spoil; (5) the cation exchange capacity; (6) quantity of gypsum; and (7) percentage of calcium carbonate present. Output consists of infiltration rate, volumes of subsurface drainage, and concentrations of calcium, sodium, magnesium, bicarbonate, chloride, sulfate, and dissolved solids in the drainage waters.

The model was tested using data from a site in southwestern Colorado. The model successfully predicted the infiltration rate and

predicting the volume of subsurface drainage. The discrepancy between measured and predicted drainage rates was attributed to the fact that the water table was less than 3 meters below the surface of the test site. When the water table is this close to the surface, the model is extremely sensitive to errors in certain parameters used to characterize the soil zone. The parameters are difficult to measure, and any measurement errors are amplified in the results. Other simulations suggest that the model will perform better for situations in which the water table is at least 3 meters below the surface.

McWhorter and others (1979) also presented a second, more practical alternative to the complex model described above. This model consists of a set of algebraic equations that are solved with the aid of a computer. The equations were derived by developing a water balance and a dissolved solids balance for the mined watershed as a whole. The model does not incorporate the chemical reactions that occur in the unsaturated zone and requires only two hydrologic parameters (f_{sm} and K) and three chemical parameters (P_{gm}, P_{sm}, and P_n) where

f_{sm} = Fraction of combined runoff that comes from the mined portion of the watershed and that occurs as overland flow;

K = The ratio of combined surface and subsurface runoff from the natural portion of the watershed to that of the mined portion;

P_{gm} = Average concentration of total dissolved solids in subsurface water in mined land;

P_{sm} = Average concentration of total dissolved solids in surface water on mined land;

P_n = Average concentration of total dissolved solids on natural land.

Woessner and others (1979) presented a materials-balance model similar in concept to the one developed by McWhorter and others (1979). Woessner and others (1979) used their model to predict the concentrations of total dissolved solids in ground water discharging from a hypothetical spoil aquifer that would be created if coal were removed from a site in southeastern Montana. They also predicted the concentration of total dissolved solids in the stream receiving the subsurface discharge. The quality of overland flow on the reclaimed land was not considered, and in this respect their model is simpler and easier to use than the one developed by McWhorter and others (1979).

These simple algebraic models, which describe water and dissolved solid balances for the watershed as a whole, are the most promising tools for routinely quantifying the effects of mining on water quality. However, the models are essentially ground-water flow models and do not include chemical reactions to account for the chemical changes that can be caused by surface mining. Incorporation of chemical reactions into models is currently a focus of research by various agencies in North America and is beyond the state of the art of models currently in use for predicting the effects of surface mining. Before models incorporating hydrogeochemistry can be used routinely,

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CHAPTER 7

CONTROLLING THE ADVERSE EFFECTS AND IMPACTS OF COAL MINING ON GROUND WATER

INTRODUCTION

The ways in which coal mining can affect ground-water resources were discussed in the preceding two chapters, along with the possible impacts of ground-water changes on ecological and social systems. Most, but not all, of the impacts are adverse, which raises the question whether anything should be done to eliminate or mitigate the impacts, and if so, what. Ground-water systems typically respond slowly to disturbances such as coal mining, and therefore the long-term consequences of potential impacts must be considered before the disturbance occurs.

The question of what to do about potential adverse impacts can be separated into two aspects. The first aspect is a technical one of defining the options available for dealing with the impacts. The second aspect is that of defining the institutional means available for employing the selected technical option. For example, a technical option available to deal with a situation in which mining causes nearby wells to go dry is to replace the water supply of the affected farms, homes, industries, or municipalities. An institutional option to bring about such replacement is to make mine operators liable for any disruption to water supplies caused by mining.

The question of whether adverse impacts should be eliminated or mitigated must also be resolved. Sometimes the answer is obvious, as when the potential adverse impact assumes life-threatening proportions yet is easily and cheaply eliminated. Another situation may involve an economic impact, such as temporary loss of limited agricultural production, which cannot be avoided without forgoing the production of coal of much greater value. Many situations are not so clear cut, however, and more difficult choices must be made. When such situations are considered, two points are worth noting:

1. A goal of eliminating all ground-water effects attributable to coal mining is irrational. To eliminate all such effects and attendant impacts is to eliminate coal mining. The

impacts of major proportions, especially in an energy-short society. No less irrational, however, would be a goal of not attempting to mitigate adverse impacts at all. Many impacts can be mitigated at costs that are lower than the value of the benefits such mitigation would produce.

2. While it is easy to identify the two extreme goals and to determine that both are irrational, it is far more difficult to determine just which of the intermediate possibilities is most appropriate. Different aids have been developed to help clarify such choices. Some of them, such as benefit-cost analysis, are discussed in detail in the report of the Committee on Soil Resources in Relation to Coal Mining (National Research Council 1981). However, such aids may be open to criticism, and none should be applied mechanically and uncritically; at best, they can provide information to assist in the selection of a choice that reflects most closely the public interest.

What is the range of choice for dealing with potential adverse effects and impacts of changes in ground water that in turn were produced by coal mining? In other words, what technical options are available? The possibilities can be categorized as follows:

Category 1. Do nothing; accept all impacts without mitigation.

Category 2. Do not attempt to modify effects, but mitigate the impacts they cause. An example is replacement of water supplies: In Pennsylvania, some coal mine operators have been replacing water supplies voluntarily for years. Nonetheless, the legislature passed an amendment to the state surface mine law requiring that an operator replace a lost water supply with water that is equal in quality and quantity to the previous supply.

Category 3. Mitigate effects (and thus impacts) by relying on the natural recovery of a ground-water system. An adverse effect observed during and after mining, for example, may become less evident with time as the natural hydrological and geochemical processes cause the system to adjust. An example of natural system recovery from the effects of underground mining was observed in Armstrong County, Pennsylvania. In 1967, Cowanshannock Creek exhibited acid and iron pollution which killed fish and rendered the stream useless. With time, the mines filled with water to a level that inundated the acid- and

system to adjust. Thus, ponds and lakes resulting from surface mining at a pre-reclamation date have recovered naturally, so that after several years some of them become good fishing lakes; still others took longer to adjust--as much as 20 years or more. In the case of underground coal gasification, laboratory research on Wyoming coals has suggested that coal may have a strong sorbtion potential for hydrocarbon byproducts of the gasification process. If this can be confirmed on a site-specific basis for other coal seams, the extent of migration of hazardous byproducts from gas generators could be considerably reduced.

Category 4. Mitigate effects (and thus impacts) by diverting undesirable outputs into more productive channels. For example, recovery of byproducts of coal may be possible. Following the 1972 flood that resulted from Hurricane Agnes, the Pennsylvania Department of Transportation us material in a local coal waste bank to rebuild approach to a bridge across the Susquehanna River in Wilkes Barre. This type of construction had previously been used successfully in England. More recently, renewed attempts have been made to reclaim coal wastes from abandoned surface and underground mines, including byproducts of coal washing. Recovery of coal from thos wastes improves both surface- and ground-water conditio by eliminating a portion of the waste products that are also sources of contamination. Recovered coal and othe waste products have been exported to Korea, to be used the manufacture of charcoal and filters.

Category 5. Mitigate effects (and thus impacts) by changing mining reclamation methods (e.g., utilizing or modifying conventional underground mining and reclamation techniques, selective placement of overburden to enhanc hydrogeologic conditions, and mine sealing.)

Pennsylvania, under its Clean Stream Law Amendment of 1965, required the mining industry to change mining methods underground, improve methods of sealing mines, and use large barriers within mines to restrict ground-water movement so as to prevent poor-quality wat from discharging into surface-water bodies following mining. The state also determined that auger mining, when conducted adjacent to an underground mine, often intercepted older mine workings and released acidic discharges to the surface. Thus, the law allows auger mining only in areas not likely to result in acid discharges.

Research is under way to evaluate both the selecti placement of overburden materials in surface mines in

planning can help control the post-mining consequences of mining. For example, if a sufficient coal barrier is left around the periphery of the mine and mining is conducted in a down-dip direction, a mine can be effectively sealed. After mining ends, the mine would flood, thereby preventing further oxidation of pyrite. Current regulations favor this technique; however, mines opened before the regulations were issued will continue to be difficult to control.

Mitigating measures adopted by underground mine operators in the West are as much in reaction to the need to continue mining as they are a result of regulations. Many mining operations there are plagued by either excessive amounts of ground-water inflow or no inflow at all. The measures used include:

- Sealing mined-out areas behind concrete walls.
- Treating pumped mine water prior to discharge into surface drains.
- Pumping water from ctive operations and discharging it into adjacent abandoned underground operations.
- Sealing the bottom of sedimentation ponds to prevent infiltration of pollutants prior to treatment and discharge.
- Avoiding the mining of areas where excessive ground water would be encountered.
- Recycling and reusing pumped mine-water in the coal preparation (coal-washing) process.

For the most part, such mitigating measures are taken at the convenience of the mining companies. Subsidence does not have the effect on residents in western mining areas that have been observed in the East and thus is not considered to be a problem.

Category 6. Mitigate effects (and thus impacts) by avoidance. For example, mining was prohibited or limited in Fayette County, Pennsylvania, in an attempt to determine whether mining could take place in the Big Stony Creek watershed without causing acid production. A subsequent analysis of overburden materials was conducted in order to make an objective determination. Because of sedimentation and siltation related to mining activities in other

quality.

The six categories are broad. The specific options under each category depend on the kind of impact to be controlled, the prevailing hydrogeologic conditions, and the mining technology employed.

INSTITUTIONAL OPTIONS FOR CONTROLLING ADVERSE IMPACTS

The first part of this chapter discussed some of the technological options for modifying or controlling impacts on the natural environment and on users of ground-water resources. To use the appropriate technical options effectively, social institutions that can encourage or compel their use must be created. The problem of institutional design and implementation is the final step necessary to ensure that ground-water conflicts, present and future, are resolved in an environmentally responsible, economically efficient, and socially equitable manner.

Control of unwanted impacts caused by the exploitation of natural resources has become a widely accepted goal of public policy. Controlling impacts that result from the ground-water changes produced by coal mining is one aspect of this concern. Much of the legislation in this area, such as the Surface Mining Control and Reclamation Act (Public Law 95-87), emphasizes the regulatory approach for constraining mining activity in order to control impacts. However, this is only one of several possible alternatives, and thus, the broader term "institutional" is used to emphasize the variety of policy choices available.

In this section, a range of institutional approaches available for controlling the impacts of ground-water changes caused by coal mining is discussed. The approaches are also evaluated from the perspective of their feasibility in relation to the characteristics of a mining situation. But technical feasibility is only one criterion for choosing a policy option, and other criteria may be just as important. The other criteria are not considered in the report, and consequently, no policy recommendations, aside from feasibility screening, are offered.

The problem of control of impacts arises because economic activity, which intentionally produces and sells valuable goods and services, also unintentionally produces additional outputs that are not marketed. Many, though not all, of the unintended outputs, side effects, or externalities represent social costs, such as air and water pollution and other forms of environmental degradation. A key characteristic of externalities is that market institutions do not automatically either encourage or reward their production if they are beneficial or discourage or penalize such production if they are detrimental. For example, those who pollute ground-water supplies, generally, do not have to bear the costs that such pollution imposes on other water users. Those costs may exceed the benefits produced by the

polluting activity. It is equally possible that pollution-control costs imposed upon polluters may exceed the benefits derived by others from such pollution control. The problem for public policy is to achieve a balance, to find that pattern of resource use which produces the best possible mixture of benefits and costs to all segments of society. Four major questions concerning decision scope, decision level, establishment of standards, and implementation can help define appropriate policy response.

Public Policy Questions

Decision Scope

The first public policy question is that of scope. For example, does it make sense to consider separate policies for controlling ground-water use and for controlling surface-water use, for considering water quantity separately from water quality, or for regulating coal mining separately from other water-related activities in attempting to achieve ground-water policy goals? If these matters are interrelated (e.g., if water moves readily between above-ground and below-ground locations), separate policies make little sense and are unlikely to succeed. On the other hand, a joint policy is both unnecessary and needlessly complicated and costly if little interrelatedness exists.

In the case of ground water in relation to coal mining, are the prospective environmental (social and ecological) impacts of ground-water changes caused by coal mining largely separate from other environmental conditions or are they part of an interrelated environmental system? Our investigation suggests that much interdependence does exist. Ground-water resources and surface-water resources are often closely interrelated. Policies, such as many state water laws, that fail to consider this interrelatedness may fail to recognize and resolve problems in which it is an important element. For example, mine dewatering through ground-water pumping could, under some circumstances, reduce surface-water supplies normally maintained in part by inflows of ground water. The situation could impair water uses dependent on those surface-water supplies. Under laws that consider ground water and surface water separately, affected users of surface water would have no protection or recourse.

Water quantity and water quality are also interdependent. Physically, reduction in water quantity can lead to increased concentrations of dissolved solids through reduced dilution alone, and the increases could lead to improved water quality. Regarding the demand reductions in water quality can become, in effect, reductions in water quantity when the polluted water becomes unsuitable for some uses. Despite this interdependence, the institutions governing water-quality control and those governing the quantitative allocation of water are usually distinct.

Water-quality control, although an area of state concern, is characterized by federal assumption of major initiatives and responsibilities (e.g., the Federal Water Pollution Control Act, the

property resource. Thus, one may acquire and own a right to use ground water, but with no assurance that the quality of the water will remain adequate for the use for which it was acquired.

Quantitative allocation of water supplies, on the other hand, is largely determined by the provisions of state water laws. Federal concern traditionally has been confined to protection of the proprietary interest of the federal government. Recent initiatives to assert a broadened federal interest, responsibility, and authority, (e.g., the Surface Mining Control and Reclamation Act) are tentative as yet. Moreover, ground water in its quantitative aspects is treated to a considerable extent as a matter of individual property rights under the laws of many states.

Similarly, coal mining and other ground-water uses are interdependent. All affect the same resource base, and the actions of every user, no matter the type of activity in which the water is used, potentially affect other users. Most of the institutional bases for ground-water management recognize and deal with the interdependence between users. In fact, the interdependence is the reason they exist.

Thus, it may be appropriate to subject one activity, coal mining, to ground-water-related restrictions that are different from and additional to restrictions applying to other activities. Such an institutional distinction would appear appropriate in the long term only if: (1) coal mining is a special and distinctively different case from other ground-water-related activities, in terms of the effects it produces, in terms of the means required to control the effects, or in terms of its importance to the nation's well-being; or (2) coal mining is in fact serving as a lead activity in a gradual shift of responsibility for control of ground-water quantity and quality from the state to the federal level, much as the Coastal Zone Management Act is seen by some as a prototype for an increased federal assumption of initiative in the general field of land-use planning; or (3) it is difficult or impossible to monitor performance, and therefore design standards, which are likely to be specific to the activity or industry, must be employed.

In any event, it is not clear that either consumptive ground-water use or ground-water-quality degradation caused by coal mining is critically different from or more serious than such changes produced by other forms of human activity. If the institutional means for allocating ground-water supplies and for protecting their quality are deficient (and they appear to be so in important respects), it is probably better to change those institutions directly than to add to them a series of ad hoc regulations concerning different ground-water-related activities such as coal mining.

An exception can be made when a particular activity, such as mining, may occur on such a scale that it potentially will radically transform and eventually dominate ecological and social conditions in an area where it is concentrated. Institutions for managing environmental quality and social change are largely suited to deal with incremental changes, not massive ones. Thus, in this special

situation, it may be desirable to invoke special institutional measures quite unlike those that apply more generally (National Research Council 1979). While this situation could be relevant to coal mining (e.g., in Appalachia or in the rapidly expanding western coal fields in Montana and Wyoming) or possibly in certain ground-water contexts (e.g., in the High Plains or the Central Valley of California), it is a situation which is beyond the scope of this study, because it does not occur as a result of impacts of coal mining related to ground water.

Decision Level

The second public policy question concerns the level of government that will formulate and implement impact control policies. Such decisions specify how much of each social cost we are willing to accept for the sake of receiving the social benefits that go with it.

In recent years, the responsibility for directing public policy for controlling environmental impacts has shifted markedly from the local and state level toward the federal level (Davies and Davies 1975). The Surface Mining Control and Reclamation Act is an example of the trend. Furthermore, responsibility for policy making can be shared in a variety of ways among several units or levels of government. The Federal Water Pollution Control Act provides for determination of broad goals at the federal level, with some objectives (which give specific meaning to goal statements) to be established at the state and local levels. The Surface Mining Control and Reclamation Act provides for both determination of the broad goals and formation of specific objectives at the federal level.

In the interest of simplicity and responsiveness to locally unique circumstances, it is preferable for decisions to be made at the lowest practical level of government. However, control can be so localized that important impacts or affected people are excluded from the decision. In such a case, all costs and benefits of a proposed development would not be considered fully. In general, then, impacts of local concern are best controlled locally, but decisions on impacts that are widespread are better made at the appropriately higher level of government. This approach, commonly known as the "problem shed" principle, has long received wide support in the literature (Davis and Whinston 1962; Kneese 1964; National Research Council 1966).

In the case of ground-water changes related to coal mining, will the prospective impacts of coal development in a particular region be expected to have major effects only upon the immediate locale in which the mining would occur, or will they be distributed more broadly, so as to have state, regional, national, or international significance?

Impacts on the ecological system, population, and social structure from ground-water changes caused by coal mining will usually be localized. However, when changes in ground-water resources affect surface water, the potential increases for broader distribution of

The existing institutional pattern of shared federal and state responsibility for controlling water quality seems generally appropriate for this situation. The concentration of responsibility for quantitative allocation of ground-water supplies at the state level could cause problems where coal mining potentially affects ground water that flows across state lines. In such cases, interstate compacts, such as those commonly used for interstate allocation of surface waters, might be considered, although the inflexibility of this approach is a major disadvantage.

Setting Standards

The third public policy question concerns the translation of goals and objectives into standards that are to guide the conduct of private individuals and business firms. Normally, goals are broad, nonqualitative statements of desired outcomes. Water quality that allows fishing and swimming, restoration of land surfaces after mining, and safe drinking water are examples. Objectives have specific meanings: An objective might be 4 ppm or more dissolved oxygen (perhaps to be attained some percentage of the time, or not to be violated for longer than a stipulated time period). Both goals and objectives pertain to environmental parameters that society desires; they say nothing about the activities of those who may affect those parameters.

Standards may be set for environmental quality itself (ambient standards), in which case they are synonymous with our use of the term "objectives." Alternatively, standards may be set for an individual or organization whose actions may affect environmental quality (Lundqvist 1974). Ambient standards can be successful only when the effects of the actions of each individual and organization upon the environment can be identified and monitored. Otherwise, individuals and organizations cannot be held accountable for their actions because the environmental consequences of those actions remain unknown. It was the absence of such knowledge that made the ambient-standards approach of the pre-1972 federal water quality legislation unworkable. For water quality, it is necessary to set standards for the individual polluter, as was done in the 1972 amendments to the Federal Water Pollution Control Act (Davies and Davies 1975). However, such standards eliminate much of the flexibility and efficiency possible with ambient standards. It has been estimated that an ambient standards approach, had it been workable, could have achieved the results produced by the approach used in 1972 FWPCA amendments approach at about one-sixth the cost actually incurred.

If the standards must be set at the level of the individual operation, should they be focused on behavior (design standard) or on results (performance standard)? Design standards focus on carrying out or avoiding stipulated practices. Performance standards set limits on permissible influences on the environment, whatever the behavior that produces or controls the influences. To reduce sulfur dioxide air ollution, for exam le, industries may be forbidden to burn high sulfur

fuels, or they may be required to install and operate scrubbers. Both are examples of design standards that control behavior. Alternatively, such industries may be required to meet emission standards that stipulate how much sulfur each plant may release (a performance standard) or that stipulates maximum permissible sulfur concentration in the receiving medium (an ambient air quality standard). Both are examples of control of the results of behavior, not of behavior itself.

Control of results is usually preferred because it permits the most flexibility and encourages innovation in finding effective ways to meet socially desired objectives. If environmental impacts cannot be measured, or cannot be traced reliably to an operation, control may be exercised at the operation itself by establishing specific emission standards; this approach, however, inevitably reduces flexibility and inventiveness. If even emissions (or more generally, the direct results of behavior) cannot be measured, the only recourse is the control of behavior through design standards, the least flexible and least efficient approach of all.

The import of such considerations for changes in ground water caused by coal mining is that if changes in ground water can be traced to specific mining or processing operations, considerable economic savings can be achieved by establishing ambient standards. If such tracing is impossible, or impossible within a reasonable timeframe, economic savings are attainable to a lesser degree through setting performance standards on the direct or immediate effects (results) produced by mining. Such an approach, for example, would limit the discharges of specific pollutants into ground-water resources. Even this type of standard may be unworkable if certain results of mining activity cannot be monitored in a timely fashion. For example, contamination of distant ground or, concomitantly, surface-water resources may not show up during the life of the mining operation. To set standards for receiving bodies such as aquifers, or for discharges to them, would be ineffectual. Only design standards can be employed in such cases, although those standards are least desirable on efficiency grounds.

Effects of coal mining on surface-water availability are relatively easy to monitor and predict. Effects on ground water are less easy and more costly to monitor and predict. Effects on ground-water quality are still more difficult to monitor and predict, particularly at some distance from the source in space and time. For new technologies, such as underground coal gasification, effects may be highly uncertain. Nonetheless, the short-term onsite effects that coal mining will produce on ground-water resources are reasonably predictable, because they do not require modeling more complex natural and social systems.

Under some conditions, contamination of ground-water resources moves so slowly that it may require many years for effects in the immediate mining vicinity to appear elsewhere. Similarly, other effects also may not show up for years, even in the mining vicinity, because the contaminants themselves do not move quickly from spoil piles into the saturated zone. In either case, ground-water monitoring will not reveal the magnitude or location of the effects, and adverse

for the changes have occurred. By then, it will be impossible to reverse the situation and prevent or modify the causal event. In addition, many measures to mitigate impacts may have become unavailable.

The socioeconomic impacts of changes in ground water related to coal mining can be monitored at the regional level, but it will be difficult to trace many of the impacts to specific mining operations. Social and economic impacts beyond the region will be mixed with so many consequences of other activities that it would be very difficult to monitor for the coal mining industry as a whole, and virtually impossible to trace to specific operations.

Those considerations suggest that the use of ambient standards would be, with rare exceptions, no more workable in controlling changes in ground water related to coal mining than it was in controlling water pollution in the 1960s. Recourse to performance standards, and sometimes even to design standards, may be necessary.

Many of the prospective ground-water changes related to coal mining are already covered to some degree by existing legislation. However, much of the legislation does not make as specific or explicit a reference to ground-water resources as would be desirable. Federal legislation that can be applied to water-quality problems includes the Federal Water Pollution Control Act, the Safe Drinking Water Act, and the Clean Water Act. Impacts upon the quantity of surface- and ground-water supplies (distinguished from qualitative characteristics of such supplies) are governed by the standards implicit in state water laws.

Implementation

The fourth public policy question concerns the type and extent of influence to be brought to bear on private individuals and business firms to ensure that they meet standards established to accomplish society's goals and objectives. What means of control should be used--providing information, creating economic incentives, promulgating and enforcing regulations, or restructuring property rights (Dahl and Lindblom 1953). In practice, a mixture of several institutional approaches may be appropriate, depending on the particular situation.

Information can be simply informative, as in giving technical assistance, or it can be intentionally persuasive. In either case, an operation is not constrained because information can be ignored. Technical information can be effective when socially unsuitable behavior stems from ignorance. Persuasion may influence behavior if the desired changes are easy to accomplish. Stronger controls are indicated when the interests of the developer and of society diverge.

Economic incentives, either rewards or penalties, may be used to "internalize" externalities (both spatial and temporal) and thus to induce voluntary compliance with social goals. Economic incentives may be created in two ways: (1) through the establishment of liability rules that define the rights and duties of private individuals or organizations; and (2) by involving government more directly either as

forms of positive incentives to encourage appropriate behavior.

Liability rules in effect require a polluter or other generator of external costs either to reduce the pollution or other form of externality, whether in part or in full, or to compensate those who bear the external costs. Such rules thus provide a framework within which market negotiations can take place between those who generate externalities and those who are affected by them. Government enters the process only as the referee which enforces the rules.

Liability rules are the most appealing form of economic incentive for many reasons, not the least of which is their ability to confine negotiations and bargaining to those who have a real stake in the matter at hand. However, liability rules tend to become impractical when many parties are affected by an externality because of the expense and difficulty in identifying all the parties, negotiating with them in a coordinated way, and compensating them. Liability rules are also subject to abuse when the possibility of threat distorts the bargaining power of one of the contending parties.

Direct government provision of economic incentives also creates economic pressure to reduce external costs (or increase external benefits). That is, government also alters the cost or revenue structures that influence the behavior of profit-making organizations. Direct incentives can take the form of taxes levied on marketed outputs, which tend to reduce production of the primary product (e.g., coal) and of the associated externalities (e.g., ground-water pollution). The incentives can take the form of taxes on inputs (e.g., high sulfur coal as a power plant fuel), which may reduce the creation of externalities more sharply than production of the final product (electricity). The incentives can also take the form of taxes on the production of externalities themselves (e.g., effluent taxes), which directly discourage the production of externalities while leaving to the firm maximum flexibility in deciding how, and even to what extent, to do so.

Tax credits and other forms of positive incentives can also be used to encourage process changes that reduce externalities. The obvious danger of such subsidies is their political appeal: Too often the desire to favor a constituent overwhelms and obscures the goal of reducing externalities and results in costly but ineffective policies.

In general, direct government provision of incentives is administratively more costly, requires more information and calculation, and is more subject to political distortion than is the establishment of liability rules. However, when the number of parties affected is large, it may be less costly and more effective than liability rules. It may be the method of choice when externalities are widely distributed or long lasting. Liability rules are effective only when those who bear, or will bear, the externalities are able to negotiate directly with those who create externalities. Obviously, future generations cannot enter into current negotiations, and thus, liability rules cannot protect their interests.

<u>Regulation</u> is an even more stringent way of obtaining socially acceptable behavior than is the provision of economic incentives.

of incentives, may invite evasions, and policing may be necessary. (An extensive discussion of the merits of the incentive and regulatory approaches can be found in Anderson 1977, Maler 1974, and Brigham and Brown 1980.)

At the extreme, restructuring property rights reallocates basic decision-making power; it relies subsequently on normal market mechanisms to achieve proper resource allocation. Rights can be shifted to other private parties through changing liability rules or to the public in general through public ownership of resources. Both accord to developers only such limited rights as may be stipulated in leases or by other contractual arrangement. Reservation of decision-making power to public agencies may be desirable under conditions of great uncertainty. Under such circumstances, a cautious, experimental approach is indicated, one that may not be compatible with the behavioral flexibility inherent in the use of economic incentives or with the delays or due process requirements of the regulatory approach.

In the case of ground-water changes related to coal mining, the foregoing considerations suggest that:

1. If the prospective environmental impacts caused by the effects of coal mining on ground-water resources are reasonably predictable and if property rights can be assigned to those impacts, a market approach employing liability rules should be considered.

2. If prospective impacts are reasonably predictable, if property rights are not easily assignable, and if some degree of flexibility in meeting standards is acceptable, a market approach emphasizing economic incentives should be considered.

3. If prospective impacts are reasonably predictable and if flexibility in meeting standards cannot be tolerated, an approach emphasizing regulation should be considered.

4. Any approach employed should include providing information on such things as technologies to control impacts wherever such information is not readily available.

The characteristics of ground-water resources, and the relationship of coal mining to them, suggest that the second approach, embodying economic incentives, be given serious consideration. Partial reliance on economic incentives, under prevailing conditions, would seem likely to produce a more efficient pattern of resource allocation at less cost, in terms of both money and social harmony. In particular, institutional measures that would require mining operators to bear the full social costs associated with the ground-water effects their mining operations create would be in order.

The difficulty encountered in assigning property rights in ground-water resources, particularly with respect to water-quality parameters, suggests that the first approach will not be easily workable. This conclusion is suggested despite the fact that the first approach forms the basis for most current state water laws. The difficulties encountered by present systems of water law (particularly as they pertain to ground water instead of surface water and most particularly as they pertain or fail to pertain to water quality) tend to support the conclusion. Sole reliance upon the third approach to controlling ground-water impacts--regulation--may also be unwise, given the generally noncritical nature of the ground-water effects of coal mining. Regulations can be costly to enforce, irritating to those who are regulated, and inefficient.

The choice of implementation approach depends in part on the characteristics of available technologies to control impacts and their relative utility and performance. Reliance on natural system recovery requires no action on the part of the mining operator and thus no institutional measures need exist to influence his behavior. Beyond that, however, action is required, and policy implementation measures are needed to initiate such action. A variety of situations, with approaches to policy implementation that might be used for each, are described below:

- When exclusion of a mining activity is determined to be desirable, it can be accomplished most effectively either through regulation (as in the provisions of PL 95-87 which designate areas as unsuitable for mining) or through public acquisition of land or surface rights. Economic incentives would be appropriate only if operators would be permitted to mine even though it would be costly for them to do so.

- When avoidance of a particular mining method is determined to be desirable, it can be accomplished most efficiently through regulation.

- When selective placement of overburden is determined to be desirable, it can be accomplished most easily by regulation. This situation uses a design standard that stipulates desired behavior rather than desired results. Economic incentives could be employed, as in the case of bonding for compliance, if an appropriate penalty for noncompliance could be determined.

- When replacement of a diverted water supply is determined to be desirable, it can be accomplished most effectively through the creation of liability rules. In this case, the potentially injured parties (those whose water supply is to be replaced) would be known and probably few in number. It should be relatively easy to make the mining operator to be liable for the costs of replacing the diverted water supply or for purchasing the right to use that water supply from its

owners if such a choice is less costly. Thus, the mining operator and the prior owners of the affected water rights would be led to maximize social net benefits.

- When mitigation of ground-water-related effects of coal mining is desirable, flexibility is tolerated, and monitoring becomes possible, then mitigation can be accomplished most efficiently through the use of economic incentives.

Existing Controls

The institutional framework for controlling the use of ground water has been described and some criteria for evaluating such a framework have been discussed. It remains to apply those criteria to existing institutions and to suggest directions for potential institutional changes that might encourage more productive resource use while placing less onerous burdens on coal mine operators and other users of ground-water resources. To understand the effectiveness of present institutional structures, it is necessary to describe one element--the Surface Mining Control and Reclamation Act of 1977--that affects coal mining, including its ground-water aspects.

The Act sets forth standards to protect ground water as follows:

> (10) minimize the disturbances to the prevailing hydrological balance at the mine-site and in associated offsite areas and to the quality and quantity of water in surface and ground water systems both during and after surface coal mining operations and during reclamation by--
>
> (A) avoiding acid or other toxic mine drainage by such measures as, but not limited to--
>
> (i) preventing or removing water from contact with toxic producing deposits;
>
> (ii) treating drainage to reduce toxic content which adversely affects downstream water upon being released to water courses;
>
> (iii) casing, sealing, or otherwise managing boreholes, shafts, and wells and keep acid or other toxic drainage from entering ground and surface waters;
>
> (B) (i) conducting surface coal mining operations to prevent, to the extent possible using the best technology currently available, additional contributions of suspended solids to streamflow, or runoff outside the permit area, but in no event

(ii) constructing any siltation structures pursuant to sub-paragraph (B) (i) of this subsection prior to commencement of surface coal mining operations, such structures to be certified by a qualified registered engineer to be constructed as designed and as approved in the reclamation plan;

(C) cleaning out and removing temporary or large settling ponds or other siltation structures from drainways after disturbed areas are revegetated and stabilized; and depositing the silt and debris at a site and in a manner approved by the regulatory authority;

(D) restoring recharge capacity of the mined area to approximate premining conditions;

(E) avoiding channel deepening or enlargement in operations requiring the discharge of water from mines;

(F) preserving throughout the mining and reclamation process the essential hydrologic functions of alluvial valley floors in the arid and semiarid areas of the country; and

(G) such other actions as the regulatory authority may prescribe; (sec 515)

J.S. House of Representatives report on Public Law 95-87 the problems of alluvial valley floors as follows:

Of special importance in the arid and semiarid coal ng areas are alluvial valley floors which are the uctive lands that form the backbone of the agricultural cattle ranching economy in these areas. For instance, in Powder River Basin of eastern Montana and Wyoming, cultural and ranching operations which form the basis of existing economic system of the region could not survive out hay production from the naturally subirrigated and d irrigated meadows located on the alluvial valley rs. In reviewing the reclamation potential of lands in West and adjusting mining to assure its compatibility existing and future land uses, the National Academy of nce study, Rehabilitation Potential of Western Coal Lands stated:

"In the planning of any proposed mining an rehabili ation it is essential to

stream channels be preserved. The unconsolidated alluvial deposits are highly susceptible to erosion as evidenced by the erosional history of many Western valleys which record several periods of trenching in the past several thousand years. Removal of alluvium from the thalweg of the valley not only lowers the water table but also destroys the protective vegetation cover by draining soil moisture. Rehabilitation of trenched valley floors would be a long and expensive process and in the interim these highly productive grazing areas would be removed from use."

(This is the quotation which appears in the House Report. It is a misquotation of the NAS report, which actually states that "these highly productive grazing areas would be in disuse".)

The House Report (H.R. 2) specifies that the operator is to "preserve throughout the mining and reclamation process the essential hydrologic functions of alluvial valley floors in the arid and semiarid areas of the country." Although the Academy study called for the preservation of alluvial valley floors, such a requirement would not recognize that under site-specific circumstances, it is possible to mine on valley floors and still be able to ensure the maintenance of the hydrologic functions of the area. Where mining is proposed on alluvial valley floors, the methods of ground- and surface-water management would have to be designed for the specific characteristics of the site and could be difficult to achieve. However, given the potential short- and long-term disruption of the affected lands and economy, this additional effort appears necessary and justifiable. Preserving the essential hydrologic functions during the mining process includes ensuring that the water balance both upstream and downstream of the mine is maintained so that natural vegetation cover is not destroyed and that the erosional balance of the area is not seriously disrupted. In addition, upon the completion of mining, the backfilling, placement of material, and grading must ensure that the hydrologic function of the area that existed before mining is continued and that the operation does not become a barrier to the movement and availability of water in the valley deposit.

Efforts by the federal government to rehabilitate alluvial valley floors that have been denuded and damaged have been very expensive, time consuming, and only partially successful. The effort to prevent such damage from occurring in the first place would have required careful planning but would have been much less expensive than later rehabilitation efforts. A number of western coal mines today plan ways to avoid damaging such valley floors and stream channels in order to reduce reclamation costs later.

The definition of "alluvial valley floor"--especially with respect to the scale and size of the deposit and the drainage area--has caused

ncern. Alluvial valley floor refers to those unconsolidated :s formed by streams (including their meanders) where the water level is so near the surface that it directly supports .ve vegetation or where flood stream flows can be diverted for rrigation. H.R. 2 defines alluvial valley floors as "the olidated stream-laid deposits holding streams where water oility is sufficient for subirrigation or flood irrigation .tural activities" [Sec. 701(27)]. In more technical terms, .l valley floors are the upper, near-horizontal surface of the olidated stream-laid deposits which border perennial, ttent, or ephemeral streams. The alluvium that makes up the -laid deposits is composed of clay, silt, sand, gravel, or detrital material that has been, or is being, transported and ced by streams. Alluvial valleys within this definition are ed by perennial or intermittent streams or by ephemeral stream .s.

Institutional Evaluation

evaluation of the adequacy of existing institutional ures--widely varying state water laws controlling ground-water wal and consumption, several federal laws (and counterparts) :ing actions that affect ground-water quality, and PL 95-87 .ng ground-water aspects of coal mining, but not of other -water uses--must be based on many considerations. :ause the members of a technical committee, such as the authors ; report, do not have the special competence or authority to judgments on many of these matters, our examination of the ng institutional structure is based on only the more technical of ny possible evaluative factors. Consequently, our examination short of recommending specific institutional changes. Our sibility is properly confined to raising questions and suggesting for subsequent consideration within the broader political :. Within that context, then, we raise the following questions the institutional structure that bears upon ground water in on to coal mining.

<u>cision Scope</u>. Should institutional control of ground-water use sidered separately from land and water use, in general, or even he gamut of public decisions embraced under "comprehensive ng"? Or should the focus be even more specific (as it now is) ering surface water separately from ground water, ground-water y separately from ground-water quantity, or even ground-water use tely industry by industry, as is done in PL 95-87? Our analysis ts that the current degree of separation fails to consider ant hydrologic and socioeconomic interrelationships and thus is to result in uncoordinated, costly, and ineffective policies. e most part, however, we have not discovered enough important lationships between water resources and other variables to

control in general, should be on industries (as in PL 95-87) or on geographic areas (as in coastal zone management). Rather, it seems desirable to enact and implement laws and programs controlling water-resource use per se; however, the laws and programs should incorporate sufficient openness and flexibility so that their application may be coordinated with other laws and programs through existing comprehensive planning at the local level and policy planning at the state and federal levels.

Decision Level. Can assignment of institutional control of ground-water withdrawals and consumption to the states and of ground-water quality control primarily to the federal government work effectively? The quantitative and qualitative aspects of ground-water supplies and uses are frequently, if not usually, interrelated. Institutional separation of responsibility for these two aspects makes coordinated treatment of them difficult.

If responsibility for control of ground-water quantity and quality were therefore consolidated at a single level of government, what would be the appropriate level? Could lodging such responsibility at the federal level be justified by spatial externalities, implying that state responsibility would lead to neglect of important impacts that transcend state boundaries? Our analysis suggests that such externalities, while they do exist, are neither common nor usually serious. Furthermore, a shift in control of ground-water allocation from the states to the federal government would encounter formidable political and legal challenges.

On the other hand, should a shift of ground-water quality control responsibilities from the federal government to state governments be contemplated? Most states have been less than vigorous in grasping this responsibility, even though they have always had the power to do so. However, states often compete with each other in attracting and holding basic industries. To gain a competitive advantage, a state might offer less stringent and less costly environmental quality control requirements. Thus, could the states be expected to adopt and implement effective ground-water quality control programs?

If the consolidation of control over both ground-water quantity and quality were judged to be best lodged at the state level, yet the states were not uniformly willing or able to discharge that responsibility, what course of action would remain? Are there means by which the federal government could encourage or require the states to assume this responsibility without imposing requirements that are insensitive to regional and local differences in both hydrogeologic and socioeconomic conditions? It is this type of influence that has been intended in recent federal legislation pertaining to coastal zone management, surface mining control and reclamation, air and water quality control, and many other areas. A comparative evaluation of programs that incorporate various means for exerting federal influence without preem ting state authority would b v l ab o curre t

cting Standards. What sorts of objectives and standards are most riate for controlling ground-water use, both in coal mining and er water-related activities? Should we attempt to set explicit ives, such as those in recent air and water quality legislation? ild we devise equitable rules for private firms and individuals low and rely upon the "invisible hand" of the market economy to us to the proper pattern of resource use?

r investigation suggests that in the field of water resources, f the many barriers to the full and effective operation of market utions are extremely difficult to overcome. The fugitive nature er (which makes it a common property resource), the large number sons affected by externalities, and the presence of substantial emporal externalities in the case of ground-water resources, all conditions predisposed to market failure. Thus, explicit ination of ground-water objectives and standards seems to be ble. The Safe Drinking Water Act has established that direction table water supplies.

if objectives and standards are to be set, should they be at bient level, at the level of the individual operator's discharges environment, or at the level of the behavior of the individual ion? Current institutions incorporate all three. Certainly standards are necessary because they express the only gful goals for public programs. No one would wish to control the outputs or the behavior of coal mine operators (or any other users) unless a sound environmental reason existed for doing d such reasons lead directly to ambient standards.

e such standards sufficient, however? They are sufficient only impact of each individual operation on the environment can be red. Current institutions provide for imperfect monitoring at nd attribution of ambient changes to individual operations is matic in many situations. Still, this is an aspect of the ity rules employed in much state water law.

rent institutions rely primarily on performance standards that l the interchange between the mining operation and its ologic environment (as is the case for many state water laws ing permits for pumping ground water and federal laws governing scharge of toxic substances). PL 95-87, however, also sets s standards, an approach that so limits flexibility and tion that it is indicated only where all else fails. Monitoring charges to and withdrawals from ground-water supplies seems lly feasible, so that the design standards approach appears to be essary with respect to the quantitative changes that result from . Some qualitative changes, however, cannot be detected by ble monitoring technology in time to forestall potential adverse s. Only design standards can be effective in such a situation.

plementation. Should implementation of ground-water-use goals rimarily on information, economic incentives, regulation, or ownership? Our analysis suggests that information, while l, will not be sufficient. A combination of meaningful economic tives, information, and regulation is needed to attain desired

goals. By contrast, current institutions make little use of economic incentives, not much more use of information, and very heavy use of regulation. Only court-made water law, to the extent that it has established and enforced liability rules, takes another tack. The thrust of existing institutions is primarily regulatory, and there is evidence that this approach is unnecessarily expensive.

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CHAPTER 8

URE NEEDS AND ABILITY OF THE HYDROGEOLOGIC COMMUNITY TO RESPOND

roughout this report, deficiencies in information, data
tion and handling, manpower, and training related to coal mining
ound water have been indicated.
this chapter those deficiencies are examined and ways of
ng them are suggested. Areas where deficiencies are likely to
ne are also highlighted.

DATA HANDLING AND COLLECTION

e Surface Mining Control and Reclamation Act of 1977 (Public Law
the Small Operator's Assistance Program in the Office of
e Mining, and state agencies currently require that hydrologic
e collected on pre-mining, mining, and post-mining conditions.
Law 95-87 contains specific requirements for monitoring and
ng the hydrology of a mined area. Data handling
sibilities cited in the Act are:

The "appropriate Federal or State agency" is to provide information on the hydrology of the general area to be mined to the permit applicant.

The permit applicant must analyze the impact of the proposed mining operation on the hydrology of the site and adjacent area.

The regulatory authority must assess the cumulative impact of all anticipated mining on the hydrology of the area.

The mine operator must monitor the ground-water and surface-water conditions at the mine site and adjacent area during mining and reclamation operations.

e draft of the Office of Surface Mining handbook for the Small
or's Assistan P gram, under "Determinati n of the Probable

Hydrologic Consequences" and "Statement of the Results of Test Borings or Core Samplings," lists the types of hydrologic data and the analyses required for each permit application. For surface water, information on seasonal stream-flow characteristics, peak flows (two storm events), low flows, flow durations, water quality, erosion and sediment load, and aquatic biology must be collected. For ground water, a well and spring inventory must be conducted; at least three observation wells must be installed, unless that requirement is waived by the regulatory agency; and data on ground-water quality and aquifer characteristics must be collected and analyzed. The information must accompany applications for mining permits. During mining and reclamation, the applicant must also monitor the effects of the mining operation and report the data to the regulatory authority.

The U.S. Geological Survey and some state agencies are assembling and disseminating hydrologic data in an attempt to meet the needs identified in current legislation. As an aid to hydrologic assessment of existing or proposed mine sites, the Survey is preparing a series of "hydrologic assessment" reports for the Eastern Coal Province and the Eastern Region of the Interior Coal Province. The reports will cover about 97 percent of all present coal mines in the United States. In addition, the Survey, in cooperation with the Office of Surface Mining, is preparing a series of catalogs that index water-data activities in coal provinces of the United States. Five catalogs will be prepared that cover the Eastern Coal Province (Volume 1), the Interior Coal Province (Volume 2), the Northern Great Plains/Rocky Mountain Coal Provinces (Volume 3), the Gulf Coast Province (Volume 4); and the Pacific Coast and Alaska Coal Province (Volume 5). The catalogs will contain information on surface-water flow, stage, and quality, and water quality in springs and wells. They also will cite areal investigations of water resources for subareas within each province. Although useful for general information, the reports are not likely to provide the comprehensive regional data assessment needed to provide a framework for collecting site-specific data at a mine site. The lack of detailed background hydrologic data in areas proposed for mining is a serious deficiency.

The permitting and monitoring process created by the Office of Surface Mining to support the Surface Mining Control and Reclamation Act will generate an enormous amount of hydrologic data. One of the major problems associated with permitting and monitoring will be processing the data for effective hydrologic assessment. According to the current regulations, a state that serves as the regulatory authority must have access to a computerized data storage and retrieval system. Systems in adjacent states should be compatible in order to facilitate the transfer of information. Moreover, the Office of Surface Mining will require access to the data in order to perform an overview of the operations within each state.

Only a few states have a computerized hydrogeological data bank. Most states will need financial and technical assistance to develop and maintain such a storage and retrieval system. Many data collected to satisfy the requirements of Public Law 95-87 will not be useful in hydrologic assessment because the quality of the data is uneven and

e critical information is missing. The data should be screened, or quality data indicated; however, states currently lack the er to process the influx of data mandated by the federal tions.

nilarly, good regional hydrologic data that are needed to provide e of reference for the collection of site-specific data to y the regulations of the Surface Mining Control and Reclamation MCRA) are lacking for many coal areas. Federal, state, and e hydrologic data collection efforts should be standardized and quality controlled. All data should be accessible for hydrologic s of a region and for coal-development assessments.

ates should devise and implement regional monitoring programs in where coal mining will be developed, with funding from federal ate sources. If necessary, the programs should be coordinated ederal data-gathering programs in coal hydrology in such agencies Office of Surface Mining, the U.S. Geological Survey, the U.S. of Mines, and the Environmental Protection Agency. State es should work with industry in devising a monitoring plan for ine to ensure that the plan meets data needs and quality rds. Attempts should be made to standardize monitoring ques (in such areas as well construction, sampling, analysis, and).

RESEARCH

search on the hydrologic effects of coal mining is not nated on a nationwide basis, and as a result, overlaps and encies in available information exist. Despite numerous ongoing ts, little information in the literature reports the effects of ining activities on ground-water quantity or quality. Techniques e developed by which alterations in the ground-water resource can dicted and adverse changes ameliorated. For example, few ts have been made to characterize disruptions in ground-water esulting from alterations of permeability. Yet, such alterations ramount in defining the environmental consequences of mining and signing, operating, and monitoring systems. Even less ation is available concerning the changes in water quality likely ur during and after mining.

an attempt to understand future research needs, the committee a consultant to survey and catalog ongoing research activities hout the nation that are related to coal mining and ground-water ces. The resulting compilation of six hundred projects was over undred pages long and is too complex to summarize effectively (Copies are available from the NRC's Board on Mineral and Energy ces.) The survey demonstrated that ongoing research efforts will rectify some of the present deficiencies in information. However, research needs have been perceived by the individual investigator ften have been biased towards particular personal interests. The wing areas have been identified by this Committee as not being

- Regional hydrogeologic studies of both eastern and western coal basins. Presently available information and ongoing research are inadequate to provide a framework for analyzing the site-specific information that will be generated during hydrogeologic assessment of existing and future mine sites. Moreover, studies on the regional geology of coal basins in the East are not comparable to those for the West. The background geologic information in the West is superior to that in the East, but the existing hydrologic data for both is inadequate. To some extent, ongoing studies by the U.S. Geological Survey Water Resources Division of 35 basins in the eastern United States and the ongoing U.S. Geological Survey regional aquifer studies may meet some of the data needs.

- Studies of water-rock interactions in aquifers to predict the effects of trace metal and organic compound scavenging in aquifers, the effects of precipitation of minerals on permeability, and the interaction of carbonate and bicarbonate waters with sulfate-rich waters. These data are needed to predict the chemical quality of ground water after mining.

- The hydrologic and chemical behavior of the unsaturated zone as it relates to the recharge process of aquifers. Special attention should be directed to the role of fractures in the unsaturated zone. Techniques are needed for determining recharge rates to natural and post-mining ground-water systems. The interaction of soil, water, and vegetation in the reclamation process has been heavily researched, but soil/water chemistry has been examined only incidentally or for major nutritive or growth-retarding components. Spoil pile hydrologic studies will be more applicable in addressing the recharge question, but the comparative data on the role of the unsaturated zone in modifying the chemistry of recharge water has been lacking. The recharge process in all aspects of ground-water basin management needs to be better understood.

- The design of artificial aquifers during reclamation, and the hydrologic systems in such spoil aquifers. Most research is currently directed toward defining the hydrologic systems in adjacent, undisturbed materials.

- The hydrologic and chemical effects of underground mine backfilling projects. Ongoing public works projects on slurry backfilling are not addressing the question of whether this technique for subsidence control will have any significant effects on ground water.

- Models for estimating effects of single and multiple mining operations on local and regional hydrologic systems. A way to quantify the process of dispersion and chemical reactions for

field techniques to determine dispersion parameters and chemical reaction terms must be developed.

Effects of pre-mining exploration drilling and mine plan drilling on hydrogeologic systems, and methods to ameliorate dverse effects of mining on ground water.

Effects of underground coal gasification on ground water, and technological controls for minimizing adverse environmental changes resulting from coal gasification.

Effects of underground mining on ground water, especially the effects of subsidence related to mine collapse. Such information will become increasingly important as the application of longwall mining techniques becomes more common in the United States.

Additional institutional means for conjunctive management of ground and surface waters, for coordinating ground-water quantity and quality control, and for incorporating long-term impact considerations into existing ground-water management institutions. Research should focus on (1) the development of creative approaches for accomplishing the three goals; and (2) comparisons and evaluations of existing and alternative institutional approaches so that the direction of institutional innovation, if not improved, will at least not be obstructed by lack of information.

Methods and applications for estimating potential impacts of ground-water changes caused by coal mining. The need for better hydrologic data and models for estimating ground-water effects has already been noted. Estimating associated social and ecological impacts is far more difficult, and the information required is even less available than that needed in estimating hydrogeologic effects. Thus, biological and social research will be needed before estimations of hydrogeologic effects can readily be used in making sound regulatory and management policies.

Alternative policies, procedures, and other institutional measures for controlling impacts of coal mining related to ground water. Presently available options are narrowly focused, insufficiently flexible, and in general, inadequately responsive to the complexities involved. Particular problems that require improved institutional treatment include (1) the selection of the appropriate level of government decision making; (2) standards that reflect the best interests of society in general and that are attainable and enforceable without an excessive burden being placed on either coal miners or enforcement agencies; and (3) application of a mixture of

incentives that will accomplish the desired results. Institutional means that will preserve as many options for the future as possible and are well-suited to decision making warrant special investigation.

MANPOWER AND TRAINING

The education of professionals in the field of hydrogeology is complicated by the fact that the subject matter is, by nature, divided between two disciplines--geology and civil engineering. The geologist has traditionally been concerned with the physical system that forms the framework for the fluids; however, until recently, the geologist has not approached the flow of fluids quantitatively. The civil engineer has taken a more quantitative approach to the study of ground water and has been concerned primarily with problems of well hydraulics and seepage through and around dams. The science of hydrogeology is a combination of these two approaches to the study of ground water. The hydrogeologist evolved from the need for a specially trained individual who could address problems caused by increased use of ground water and problems related to ground-water contamination.

In general, a professional hydrogeologist or geologist must have the master's degree or equivalent experience. For geologists, the master's degree is considered to be the professional working degree, although in recent years, registration or licensing in a number of states is requiring several years of experience, also. A civil engineer, on the other hand, must be licensed by a state-regulated program that generally requires four years of training past the bachelor's degree. Professional geologists or civil engineers who serve as hydrogeologists, therefore, will have either the formal education at the master's level or equivalent experience in government or industry.

The fact that many private, state, and federal positions for hydrogeologists go unfilled, despite competitve salaries, indicates that the number of available, appropriately trained hydrogeologists is inadequate. The ability to produce enough well-trained hydrogeologists is hampered because the programs available are limited in scope, and most civil engineering and geology departments in which the programs are offered consider ground-water hydrology less important than the overall programs. Another factor is that the interdisciplinary nature of the subject means that a student needs a combination of courses, not all of which will be available at most universities. Currently in the United States, only seven programs have more than two faculty members who are actively involved in a program in hydrogeology. The fact that most programs have only one faculty member characterizes the state of education for hydrogeologists in the United States.

Future hydrogeologists must contend with opposing philosophies of employers and educators: employers declare that universities do not train hydrogeologists to solve practical problems, while universities maintain that application to specialized problems should come with the job. In other words, hydrogeologists need ractical training prior to

ort courses (such as university extension courses, adult
ion, and professional training) are means by which current
encies in training may be corrected. Coal hydrology is only one
y areas of hydrogeology where teachers are needed and for which
g staff are inadequately trained. Many companies are attempting
l positions in hydrogeology by shifting those trained in other
ts (e.g., chemistry, physics, biology, or engineering) to address
-water problems. Persons involved in such shifts need both short
s in basic principles of hydrogeology and specialized training.
er, hydrogeologists trained in traditional university programs
in most cases, lack training in one or more of the following
hydrogeochemistry, field methods, modeling techniques, applied
sics, soil physics, and soil chemistry. A well-planned,
unded, well-run series of short courses covering these and other
in basic hydrogeology is needed to fill existing gaps in
ng. Short courses are also needed to provide training in various
d and specialized areas, such as mining hydrogeology and
ort of contaminants from waste disposal sites. The U.S.
ical Survey Training Center in Lakewood, Colo., should be
ctured and opened to a broader array of Geological Survey and
candidates. Training in coal hydrology, however, will be
ed by the deficiencies in knowledge discussed in the preceding
n.

his discussion of manpower needs and of the adequacy of available
sity programs to meet the need for hydrogeologists has been based
e experience of Committee members. Further quantitative
ation of future manpower needs and of the ability of universities
et them should receive high priority.

BIOGRAPHICAL INFORMATION

MEMBERS OF THE COMMITTEE

DAVID A. STEPHENSON has a Ph.D. in hydrogeology from the University of Illinois. He was professor of hydrogeology at the University of Wisconsin at Madison and was Chief of the Water Resources Section, Wisconsin Geological Survey. In his joint appointment with the university and the State Geological Survey, Dr. Stephenson conducted research on quality of water resources, with particular emphasis on proper management and use of surface- and ground-water resources and the use of ground-water systems for industrial and municipal water supplies. He is now Chief, Water Resources Section of Woodward-Clyde Consultants Western Region Office, San Francisco.

ALLEN F. AGNEW has a Ph.D. degree in geology from Stanford University. Before joining the Congressional Research Service of the Library of Congress, he worked in economic geology with the Illinois State Geological Survey, and in mining and ground-water geology with the U.S. Geological Survey and South Dakota Geological survey--where he also served as State Geologist. Dr. Agnew has taught at the Universities of Alabama and South Dakota, and he directed the Water Research Centers and taught at Indiana University and Washington State University. He is a generalist in ground-water resources management, with expertise in coal surface-mining hydrology.

MARY P. ANDERSON has a Ph.D. Degree in hydrogeology from Stanford University. She taught at Southamptom College of Long Island University, New York, from 1973 to 1975, and since then has been at the University of Wisconsin-Madison, where she is an associate professor of geology. Her field of expertise is modeling ground-water flow systems.

WILLIAM H. BAKER was trained in civil engineering and water science at the University of Illinois. He worked for 17 years with the Illinois State Water Survey and with Amax Coal Company for 2 years before becoming a consultant in 1977. He is experienced in research and development in the field of water resources and in the application of regulations designed to protect those resources.

M. BRIMHALL holds B.S. and M.S. degrees from the New Mexico
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A&M University, where he is conducting reseach on environmental
chnological aspects of in-situ gasification of coal, Mr. Brimhall
years of industrial experience with water and energy resources
western United States.

T. CARUCCIO has a Ph.D. degree in geology from Pennsylvania State
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New Paltz. Dr. Caruccio is an expert on effects of Appalachian
ining on ground-water quality, especially regarding acid mine
ge.

. CHERRY has a Ph.D. in geology from the University of Illinois.
on the faculty of the University of Manitoba from 1967 to 1971
s been at the University of Waterloo since then. Dr. Cherry is a
list in geochemistry and the effects of western coal mining on
-water quality.

T H. DREESZEN has an M.Sc. in geology from the University of
ka. He has been with that university since 1949 where he is
or of a division that includes state geological and ground-water
s. Mr. Dreeszen's expertise is in optimum use and management of
resources with emphasis on ground-water quality and quantity.

S G. GROAT has a Ph.D. degree in geology from the University of
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ic Geology from 1968 to 1976. He became the State Geologist for
ana in 1977 after serving as Chairman of the Department of
ical Sciences at the University of Texas at El Paso for one and a
ears. Dr. Groat's expertise is in environmental aspects of
with emphasis on lignite mining in the South.

R. LEAVITT has a B.S. degree in geological engineering from
n Technological University and holds a Professional Engineering
ration in the Commonwealth of Pennsylvania. Before joining
idation Coal Company as a hydrogeologist in 1978, he worked for
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erienced in developing and assessing hydrologic data for use in
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ring of ground-water quality and quantity.

B. LORD has a Ph.D. in natural resource economics from the
sity of Michigan. He was on the faculty of the University of
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JAMES B. MACDONALD has a law degree from the University of Wisconsin. He has been on the faculty of the University of Wisconsin Law School since 1954 and the Institute for Environmental Studies since 1970. He specializes in environmental and water law, with emphasis on allocation of water rights and legal aspects of resource development.

WAYNE A. PETTYJOHN has a Ph.D. degree in geology from Boston University. He served with the U.S. Geological Survey from 1963 to 1967 and was at Ohio State University from 1967 until he joined Oklahoma State University in 1980. Dr. Pettyjohn, an attorney, is experienced in ground-water quality, legal aspects of water law, and mapping strip mines.

LYLE V.A. SENDLEIN has a Ph.D. degree in geology and soil engineering from Iowa State University where he taught and was a co-director of the Iowa Coal project until he went to Southern Illinois University in 1977. Dr. Sendlein is experienced in applying hydrology and geology to practical engineering problems, such as coal mining. He is also skilled in planning investigations of ground-water pollution resulting from such disturbances as landfills and mines.

DAVID A. SOMMERS has a Ph.D. degree in geology from the University of Massachusetts at Amherst. Before joining Hydrosciencs, Inc., he was a senior hydrogeologist with Dames and Moore and before that, Director of Hydrology with Woodward-Clyde Consultants. Early in his career, he worked for the Montana Bureau of Mines and Geology and the U.S. Geological Survey and was a professor at the University of South Florida and at Rennselaer Polytechnic Institute. Dr. Sommers has experience in the planning and directing of many baseline hydrological studies and impact analyses for both surface and subsurface coal mines in the western United States.

D. RICHARD THOMPSON has an M.S. degree in geology from Miami University. Before joining the Division of Mine Drainage Control and Reclamation for Pennsylvania in 1966, he worked with the Texas Water Development Board as a hydrogeologist. Mr. Thompson's expertise is in impacts of eastern coal mining on ground water and in restoration of aquifers.

WAYNE VAN VOAST has an M.S. degree in earth sciences from Montana State University. He was with the U.S. Geological Survey in Minnesota as a hydrologist from 1965 until 1969 when he joined the Montana Bureau of Mines and Geology. He is an Associate Research Professor at the Montana College of Mineral Science and Technology and, since 1971, has specialized in studies of hydrogeological impacts of western coal mining and technology for restoring aquifers subsequent to mining.

WILLIAM WOESSNER has a Ph.D. degree in hydrogeology from the University of Wisconsin and has been with the Desert Research Institute since 1978. Before joining DRI he was project manager-hydrogeologist for a 3 1/2 year coal-water resource study on the Northern Cheyenne

tion, Montana. He is experienced in hydrological and
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S. YARE has an M.S. degree in geology from the University of
usetts. Before joining Peabody Coal Company in 1977, he worked
round-water consultant on Long Island, New York. He is
nced in the protection of aquifers in mined areas and in
r rehabilitation.